Cosmology in the year 2003

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Brief History of the Universe – Reader’s Digest Version!

10^{-44} second: Planck time – we don’t know anything before this time

10^{-35} second – 10^{-30} second (??? no one really knows for sure): INFLATION ERA

~ Quark Soup Era ~

particles, antiparticles, and radiation exist in equilibrium

10^{-7} second: p/p-bar and n/n-bar production stops

Somewhere in here neutrinos decouple

~ .75 second: e^-/e^+ production stops

~ 1 second: Nucleosynthesis begins
~ 3 minutes: Nucleosynthesis ends – Universe is filled with positively-charged light nuclei, electrons, and photons.

~ Photon-Baryon Fluid Era ~

acoustic oscillations echo through the plasma-filled Universe

~300,000 years: Matter and radiation first decouple; first neutral atoms form; origin of the CMB

~ 200,000,000 years: First stars form

~ 1,000,000,000 years: First galaxies form

~13,700,000,000 years: TODAY
Nucleosynthesis $t = 1$ sec to 3 min

First neutral atoms form at $t = 3 \times 10^5$ yrs

Origin of the CMB

First stars form at $t = 2 \times 10^7$ yrs

First galaxies form at $t = 10^9$ yrs

Solar System form at $t = 9.2 \times 10^9$ yrs

Humans appear on Earth, $t = 13.698 \times 10^9$ yrs

age "now" = 13.7 Gyr
We live in a very special time!
The Universe seems to be critically balanced between open and closed.
How can we tell the shape of space?

One way is by looking at something very distant whose actual size you can predict, and comparing its angular size now to what you expect it would have been at the time that the light left its source.

As we’ll see, small-scale temperature variations in the CMB provide a means of checking this...
Another way the shape of space can be determined is from its expansion rate which, as we’ll see, depends on the total matter and energy content.

- **open?**
  - expansion energy > gravitational potential energy
- **flat?**
  - expansion energy = gravitational potential energy
- **closed?**
  - expansion energy < gravitational potential energy
THE HISTORY AND FATE OF THE UNIVERSE

Eight major stages in the evolution of the universe are illustrated below.

Our Cosmic Address

Learn more at UniverseAdventure.org and at CPEPweb.org

See text for details.
Density = Destiny
If the Universe has a certain Critical Density, then the expansion velocity is exactly balanced by the gravitational attraction of all the matter in the universe, and we will asymptotically approach zero expansion velocity...

\[ \rho_c = \frac{3H_0^2}{8\pi G} \]

...or so we used to think...
Contributions to the total density of the Universe:

\[ \rho = \rho_{\text{baryon}} + \rho_{\text{radiation}} \]  
...pre-1980...

\[ \rho = \rho_{\text{baryon}} + \rho_{\text{radiation}} + \rho_{\text{darkmatter}} \]  
...since 1990, at least...

we now have reason to believe that...

\[ \rho = \rho_{\text{baryon}} + \rho_{\text{darkmatter}} + \rho_{\text{radiation}} + \rho_{\Lambda} \]  
...where \( \Lambda \) is the energy density of space itself, or so we think...
“Omega” is the dimensionless density parameter, the ratio between the density of any component of “stuff” in the Universe to the critical density needed to keep the Universe flat.

\[ \Omega_x = \frac{\rho_x}{\rho_c} \]

\[ \Omega_{\text{baryon}} + \Omega_{\text{darkmatter}} + \Omega_{\text{radiation}} + \Omega_\Lambda = \Omega_0 \]

If \( \Omega_0 = 1 \) this implies that the geometry of the Universe is FLAT even with Lambda...
So far, all indications seem to be:

\[ \Omega_{\text{baryon}} + \Omega_{\text{darkmatter}} + \Omega_{\text{radiation}} + \Omega_{\Lambda} = 1 \]

- "normal" stuff
- radiation, which was important in the early Universe, but is now negligible
- stuff that we now know exists by its gravity but we can't see it
- mysterious vacuum energy density
but...
The final accounting seems to be:

5% Ordinary Matter
25% Dark Matter
70% Dark Energy
Most of the “stuff” of the Universe is in some dark, non-luminous form -

*Dark Matter* and *Dark Energy*...

but we don’t really know what either really is!
A typical galaxy has $\sim 10^{11}$ times the mass of the Sun, but only $\sim 10^{10}$ times the luminosity, so there is 10 times more mass than we can see.

**Dark Matter:** interacts gravitationally, but does not shine.
Galaxy rotation curves - the first clues about dark matter

\[ v(r) \]

what we see:

\[ v(r) \]

what we would expect, if most of the mass were concentrated in the galactic center:

We can tell from the rotation curves of spiral galaxies that most of the mass of the galaxy is not merely concentrated in the core, where the luminosity is greatest, but surrounds the bulge and spiral arms in a dark, spheroidal halo.
Vera Rubin was the first to discover that galaxies did not follow Keplerian rotation curves, which led to the discovery of DARK MATTER.
Gravitational Lenses - more evidence for dark matter
We know that mass bends spacetime, and light follows the curvature of space, so when we see distorted images, we know there is some unseen mass that is causing the distortion.
but... what is dark matter made of?
Massive Compact Halo Objects

One type of dark matter candidate that has been searched for over the past decade or so are the MACHOs.

Two groups began searching for MACHOS in the early 1990's - one group looked toward the center of our galaxy, the other toward the Large Magellanic Cloud.
Temporary brightening of a star due to the passage of a MACHO

Conclusion: MACHOS can account for only ~ 10%
Weakly-Interacting Massive Particles

WIMPs are the other dark-matter candidates, thought to be a new type of subatomic particle. People hope to detect it by its scattering products, when it occasionally bounces off a heavy nucleus, using huge detectors like this one at Fermilab...
but...

What about the other 70%?

5% Ordinary Matter
25% Dark Matter
70% Dark Energy
Where does this repulsive energy come from...
Quantum Mechanics predicts that empty space itself contains a “foam” of virtual particles and antiparticles that are constantly popping into existence and mutually annihilating each other in a time scale too short to be measured!

The energy of empty space is NOT zero!

This has been called the VACUUM ENERGY DENSITY.
Casimir Effect: *a physical manifestation of zero-point energy*

...made of the same “stuff” as $\Lambda$?
In fact, at distances below a micrometer the Casimir force becomes the strongest force between two neutral objects. At separations of 10 nm - about a hundred times the typical size of an atom - the Casimir effect produces the equivalent of 1 atmosphere of pressure.

A tiny metallic sphere is brought near to a plate of the same metal. An attractive Casimir force causes the cantilever to bend. This bending is monitored by bouncing a laser off the top of the cantilever and using photodiodes to record the reflected light in this experiment, using an AFM.
We now believe that this *Lambda* (also called vacuum energy density, dark energy, phantom energy, or quintessence) is a PROPERTY OF SPACE ITSELF. It may have caused the initial *inflation* of the Universe...
Scale of the Universe

Inflationary Epoch

Inflationary Model

Radius of Observable Universe

Standard Model

radius (meters)
age (seconds)
How does the density change as the Universe expands?

Matter density (baryonic and dark) decreases as \((1/r^3)\)

Radiation density decreases as \((1/r^4)\) because wavelengths are also stretching as space expands.

Vacuum energy density remains CONSTANT as space expands, because it is a property of space itself!
Since the vacuum energy density remains constant, as the volume of the universe increases, the total vacuum energy increases, causing the expansion rate to **ACCELERATE**.

*Maybe one day it will totally overcome gravity and even the nuclear forces, and everything will fly apart in the Big Rip!*  

*...in another $10^{22}$ billion years...*
And, there is a growing body of evidence indicating that the Universe may be entering an acceleration phase!
Clue #1: Mismatch in distance calculation for Type Ia Supernovae based on their red shifts and distance moduli.
Clue #2:
Ages of globular clusters indicate that the Universe must be older than 10 - 12 Gyr,

*but...*

M13
(HST image, WFPC2)
A high value of \( H_0 = 72 \) indicates an age of less than 10 Gyr if one assumes a constant rate of expansion and no vacuum energy.

(figure from Krauss, 2003)
Clue #3:
CMB Power Spectrum:

Small-scale variations in the microwave radiation of the Universe indicate that the universe IS flat, lambda-dominated, and is currently expanding at a rate of around 72 km/sec/Mpc.
Cosmology and Relics of History

*Cosmology* is the study of the universe as a whole. As in archaeology, cosmology finds clues to the past in relics. Looking out a distance $d$ in space is looking back in time, because $t = d/c$ (light travels at a finite speed $c$). The laws of nature discovered on Earth can be applied to the early universe and tested by observing relics.

**A Relic from the Early Universe**

The Cosmic Microwave Background (CMB) is a universal bath of lightwaves (photons) from the hot dense, early universe. They are stretched by the expansion of space. To a part in 100,000, the CMB is the same no matter where you look (it is isotropic). The remaining tiny variations (shown in figure) are images of the seeds that later form galaxies and larger cosmic structures.

This is an image of the universe from the time when atoms first formed. It is a map of the entire sky showing CMB light with the uniform part subtracted.
In the early 1960's Arno Penzias and Robert Wilson, then at Bell Labs, noticed a small discrepancy in their microwave instruments that indicated an excess of radiation coming in from space. Not content to ignore it, they soon made one of the profound discoveries of the 20th century: they had found the embers of the early universe.
When viewed in the light of Edwin Hubble's discovery of the redshifts of galaxies some 30 years earlier, this microwave background could be nothing other than the highly red shifted and cooled relic radiation from a very hot infant universe, now seen at a black body temperature of around 3 Kelvin. Black body spectrum of CMB peaks at wavelength ~ 1 mm
This radiation is due to the CMB photons that are now arriving from the “last scattering surface”, red shifted by a factor of 1000 or so.

About 1% of the “snow” on a tv is due to CMB photons.
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

S.G. Djorgovski et al. & Digital Media Center, Caltech

Cosmic Microwave Background Radiation
BIG BANG SINGULARITY
SURFACE OF LAST SCATTERING
HERE AND NOW

- $Z = 1$
- $Z = 3$
- $Z = 1000$
This is the origin of the CMB... which was first measured in ~1965 at about 2.73 K, smooth to one part in $10^{-4}$. 

COBE DMR Microwave Sky at 53 GHz
In 1992, data from the Cosmic Background Explorer satellite, launched by NASA in 1989, showed evidence for minute temperature variations (anisotropy) in the CMB at a level of just one part in $10^5$, at angular scales around $10^o$ or so.

The COBE sky at 53 GHz
• For reference, 10 degrees of arc on the sky is about the angle subtended by a typical fist at arm’s length.
But the really interesting information comes from an angular size of about 1 degree...
1998-1999: BOOMERANG circled the globe over the South Pole, mapping the sky at microwave frequencies, at an angular resolution of 1°.
The sky at 150 GigaHz (~2 mm)
The sky at 545 TeraHz (~550 nm)
the "horizon" at that time corresponds to

1° of arc on the sky today
Variations in the temperature of space have precisely the size we would expect if the shape of the Universe is FLAT!
Wilkinson Microwave Anisotropy Probe

launched in 2000 into a very high-altitude earth orbit to map the entire sky at an angular resolution of $1^\circ$ or better, in 5 frequency bands

The WMAP sky at 53 GHz
...and as our measurements increase in accuracy and precision, all indications seem to be that we live in a geometrically flat, lambda-dominated, accelerating Universe, which is about 13.7 billion years old.
How will it all end?

$H_0 = 70 \pm 5$

$t_0 \approx 13\text{Gyr}$

$\Omega_b = 0.045 \pm 0.015$

$\Omega_M = 0.3 \pm 0.1$

$\Omega_{Total} = 1.03 \pm 0.1$

$\Omega_{\Lambda} = 0.7 \pm 0.1$

$\omega \leq -0.7$

data taken from
L.M.Krauss, 2003