Cosmology: the History of the Universe

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A preliminary warning:

COSMOLOGY IS NOT COSMETOLOGY!

**Cosmology:** The science or theory of the universe as an ordered whole, and of the general laws which govern it. Also, a particular account or system of the universe and its laws.

**Cosmetology:** The art and practice of beauty culture
Things people have *always* wanted to know about the Universe

- Did it exist forever or it had a beginning?
- Is it finite or infinite?
- What is it made of?
- How is it going to end?
Cosmology today is a science that has some answers to these questions. Let us see them.
Birth of modern ("scientific") cosmology

- 1905-'16: Einstein formulates his theory of General Relativity

Laws that describe gravity for very big, very dense, very fast objects

- 1917: he tries to apply his theory to the whole Universe

Did the Universe have a beginning?
What does he get from his equations?

The Universe should be expanding!

...but at that time, people were thinking that the Universe was static...

Einstein concludes that his equations must be wrong:

He adds them an extra term (the **cosmological constant**) to get a static Universe

Did the Universe have a beginning?
...a few years later (1929) Edwin Hubble discovers that galaxies are going away from us with a velocity proportional to their distance!

Did the Universe have a beginning?
This is exactly what we expect to see if the Universe is expanding

(More or less the same thing that you would see if you were a raisin in a cooking raisin cake and you were looking at the other raisins)

$t=0$

$t=1$ hour

Did the Universe have a beginning?
...and so Einstein was right in his first result

and was wrong when he modified his equations, adding the cosmological constant

The biggest blunder of my life
If things are flying away from each other, it means that they should have been closer to each other in the past.

there was a moment when the Universe was **infinitely dense**!

**Big Bang!**

(about 14,000,000,000 years ago...)

Did the Universe have a beginning?
Did the Universe have a beginning?
Is it finite or infinite?

The speed of light is finite (299,792,458 m/s) &
The age of the Universe is finite (~14 billion years)

We can only see a finite portion of Universe

It has no sense to ask what is at larger distances
We cannot know whether the Universe is finite or infinite
What is it made of?

Of course, of the same stuff WE are made of!

Neutrons, protons, light, neutrinos, electrons...

Is this all?
Galaxy rotation curves

In the ‘30s people started measuring the speed of stars that rotate around galaxies.
The velocity of the star depends on the quantity of matter between the star and the center of the Galaxy:

Newtonian attraction to the center of the galaxy

\[ = \frac{GmM}{r^2} \]

Centrifugal “force”

\[ = \frac{mv^2}{r} \]

equating them: \( v = \sqrt{\frac{GM}{r}} \)
Results of measurements:

$v(r)$ if there was only luminous matter in the galaxy

measured $v(r)$
Zwicky (1933): galaxies live in a halo of DARK MATTER

Dark matter behaves like dust
It is not ordinary matter
We do not know what it is
(but we have candidates)

It interacts very weakly
(if at all) with ordinary matter

Galaxies contain roughly five times more dark matter than ordinary matter
How do we imagine the dark matter halo:

Note: this is an artist’s view! Since we have not observed dark matter, we do not have pictures of halos!
What does theory tell us?

We quantify the amount of matter per unit volume by defining a quantity called $\Omega$

$\Omega=0 \Rightarrow$ no matter at all

$\Omega<<1 \Rightarrow$ low matter density

$\Omega>>1 \Rightarrow$ high matter density

Ordinary matter + Dark matter give $\Omega \approx 0.3$
Why do we care about $\Omega$?

Because it depends on time, and $\Omega=1$ is an *unstable* equilibrium point: evolution of the Universe brings $\Omega$ away from 1.

If $\Omega$ is close to 1 today, it should have been **VERY** close to 1 in the past!
If $\Omega=0.3$ today, then $\Omega$ should have been equal to $0.99999999999999999993$ when the Universe was 1 second old!

Much more elegant to assume $\Omega=1$, always

...but where is the remaining matter that allows us to go from $\Omega=0.3$ to $\Omega=1$? 

A mystery until 1998

What is it made of?
ABSTRACT

We report measurements of the mass density, $\Omega_m$, and cosmological constant density, $\Omega_k$, of the universe based on the analysis of 42 Type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 1.2, are used jointly with a set of supernovae from the Caltech-Tololo Supernova Survey, at redshifts below 0.1, to yield a Hubble constant $H_0 = 72 \pm 10$ km/s/Mpc at the 95% confidence level.

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae in the range 0.16 < z < 0.28. The luminosity distances of these objects are determined from Type Ia supernovae and a set of Hubble's constant parameter $H_0$ and the cosmological constant $\Omega_m$. The data are consistent with a flat universe (Hubble constant $H_0 = 76 \pm 10$ km/s/Mpc) and a cosmological constant $\Omega_m = 0.7$. We also find that the expansion rate has decreased by a factor of 2 since the time of the supernova burst.

Key words: cosmology: observations -- distance scale -- supernovae: general
What did they look at: expansion of the Universe

What is it made of?
We call $\Omega_M$ the contribution to $\Omega$ from ordinary + dark matter (we know $\Omega_M \approx 0.3$).

We call $\Omega_\Lambda$ anything else... so that

$$\Omega = \Omega_M + \Omega_\Lambda$$

They find that indeed $\Omega = 1$!
We have no idea what this stuff is, neither we know what it looks like.

We do not know what it is, but we have an idea how it looks like.

We know exactly what this part is.

What is it made of?
What are the properties of DARK ENERGY?

- It is smoothly distributed EVERYWHERE (everywhere there are about $10^{-29}$ g/cm$^3$ of dark energy, i.e. this room contains about $10^{-20}$ g = 0.00000000000000000001 g of dark energy)

- It looks a lot like Einstein’s cosmological constant

- It does not dilute away as the Universe expands
How is it going to end?

Well, do not know!

...but if dark energy is really something that does not dilute away, eventually the Universe will end up being basically empty all other forms of matter will have diluted away, and we will be left with a Universe full only of dark energy.

No Galaxies, no Stars, no Planets...
...but we have about 100,000,000,000,000 years
...quite sad...
before we start worrying!

How it is going to end?
What can we do in the meanwhile?

Try to understand better what is out there!

☛ With accelerator experiments
The Large Hadron Collider in Europe will start taking data in 2007. It might produce dark matter particles.
What can we do in the meanwhile?

Try to understand better what is out there!

» With accelerator experiments
» With astronomical observations
Many new observations are expected in the next few years to further improve our knowledge of what is out there
What can we do in the meanwhile?

Try to understand better what is out there!

- With accelerator experiments
- With astronomical observations
- With more refined theories
Sometimes Theory can get where experiments cannot get!
Conclusion

• Cosmology tells us many things about the Universe

• Now we know how much matter is out there

• We still have to understand WHAT is the 95% of all matter in the Universe