Introduction to observational Cosmology

1/3- From the static universe to the Big-Bang

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Newtonian cosmology?

1684 Universal law of gravitation

1687 *The mathematical principles of natural philosophy*
  Basis of classical mechanics
  Assumes the existence of absolute space and time

- Stars are considered as fixed
- Newton explores the possibility of finite and infinite number of stars
  - Stars must be very distant
  - Precise balance of gravitational forces
  In both cases Newton refers to God to assure the stability of the universe.
  In essays of cosmology in the 18th century, strong links with theology..
- Most common was the idea of an infinite distribution of matter in infinite space.
An infinite stellar universe? – The Olbers paradox (1823)

Why is the night sky dark?

Heinrich Olbers (1758 – 1840)
Luminosité $L$

$D$

Surface collectrice

Emitted and measured flux

$L$: luminosity emitted by a source [W] or [J.s$^{-1}$]

$F$: flux or energy received per surface unit and per second [W.m$^{-2}$]

$$F = \frac{L}{4\pi D^2}$$
\[ n = \text{density of stars} \]
\[ L = \text{luminosity of 1 star} \]

Luminosity of a shell:
\[ n \times 4\pi R^2 \times dR \times \frac{L}{4\pi R^2} = nL \, dR \]

Independent of \( R \)!

Total luminosity diverges
Olbers’ solution:

The universe is not perfectly transparent (cf. On the transparency of space, 1823)

Note that this solution is problematic as any absorber would eventually re-emit radiations, which would have already occurred in an eternal universe.
Alternatives:

- Matter is not uniformly distributed in space?
- Light looses energy while travelling?
- The universe has an origin?
- ....?

Some of these assumptions were developed in the 19th / 20th centuries, but only the framework of General Relativity allowed to bypass the paradox.

Read Edgar Poe, *Eureka* (1848) on this topic where many intuitions of 20th century cosmologies are already present.
Towards the idea of an expanding universe
The Big-Bang models

Observations supporting these models:
- The recession velocity of galaxies
- Ages of universe contents
- Primordial nucleosynthesis
- Cosmic Microwave Background

Theory
- GR (1917)
The first nebulae surveys

Charles Messier (1730 – 1817)

103 nebulae published in 1781

William Herschel (1738 – 1822)

2500 nebulae published in 1802
Charles Messier about galaxy M65 in the Lion constellation:

« Very faint nebula that does not contain any star (...) »
The telescope of William Herschell (1789)

Focal length : 12m
Aperture : 122 cm
The Leviathan of Parsonstown (Lord Rosse) 1842-1845

Aperture: 183 cm
Focal length: 17m
From nebulae to galaxies

Reproduction of Lord Rosses’s drawings in a plate extracted from an article of Stephen Alexander published in 1852.
What is the nature of nebulae?

- **Emmanuel Kant**, *Universal natural history and theory of heavens* (1755).
  Nebulae could be large collections of stars, other island universes.

- **Curtis – Shapley**, the great debate (1920’s)
  Are nebulae outside or inside the Milky Way?
Spiral nebulae are « galaxies »

Hubble shows in 1929 that spiral nebulae are

- external to the Milky Way
- recede from us

The 2.50m Telescope of Mont Wilson in California

Edwin Hubble
In this image of M31 (1923), Hubble marked 3 novae – among which one was revised (VAR!) as a cepheid.

M31 was found to be at a distance of 2.5 millions L.Y. from whereas the Milky way size is ~100,000 L.Y.
Distance of Cepheids

\[ M = f(T) \]

Relation established in 1908 by Henrietta Lewitt while studying cepheids in the Magellanic clouds.

1. measure \( T \)
2. derive \( M \)
3. measure \( m \)
4. derive Distance from \( m-M \) \( (m-M = 5\log(D) - 5) \)
Galaxies are receding

• 1914 – 1921 Measurements of nebulae spectra by astronomer Slipher: discovery of « red » shifts for many galaxies.
• 1929 Hubble established a relation between radial velocity \((V=cz)\) and galaxy distances.
Hubble’s law (1929)

Velocities derived from spectral line shifts.

[ Vesto Melvin Slipher 1923 ]
[ Milton Humason ]

Distances measured from the L-T relation of cepheids.

[ Henrietta Leavitt ]

\[ V = H D \]
For the classical Doppler effect $z = \frac{V}{c}$ where $V$ is the relative radial velocity of the source.

Redshift

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e}$$

$\lambda_e$ is the emitted wavelength

$\lambda_o$ is the observed wavelength
Ca II: 393 & 397 nm [Ionised Calcium]
H I: 410, 434, 486 & 656 nm [Atomic Hydrogen]
Mg I: 518 nm from Mg I [Neutral Magnesium]
Na I: 589 nm from Na [Neutral Sodium]
Geometrical properties of Hubble’s law

\[ t \to t + \Delta t \]

\[ D \]

A_0, A_1, A_2
Propriétés de la loi de Hubble

\[ t \]

\[ t+\Delta t \]

\[ A_0 \rightarrow A_1 \rightarrow A_2 \]

at \( t \): \( A_0A_1 = D, \ A_0A_2 = 2A_0A_1 \) and \( V_{1/0} = H.D, \ V_{2/0} = H.2D \)

at \( t+\Delta t \) : \( A_0A_1 = D+V_{1/0}\Delta t = D+HD\Delta t = D(1+H\Delta t) \)

\( A_0A_2 = 2D+V_{2/0}\Delta t = 2D+2HD\Delta t = 2D(1+H\Delta t) = 2A_0A_1 \)

\( \Rightarrow \) homogeneous dilatation of space
La loi de Hubble conserve les distances et les angles.
Expansion of the Universe

Galaxies at $t_1$  Galaxies at $t_2$
2 observers in different galaxies observe the same V=HD relation.

This is the case only for a linear relation between V and D.
Cosmological redshifts correspond to a « stretch of the light » while travelling.
Cosmological Redshift

Classical Doppler :
It is the relative motion of the source that produces the spectral shift

Cosmological expansion
It is the expansion / contraction of space that produces the spectral shift
Cosmological redshifts are due to the contraction/dilatation of space

Let’s assume a distant source emits a radiation with wavelength $\lambda_{emit}$ when the universe was more contracted relative to now and characterized by a contraction factor = «a» (<1). («a» is called scale factor)

If our present scale factor =1, the observed wavelength is

$$\lambda_{obs} = \lambda_{emit}/a$$

and

$$1 + z = 1/a$$
In general, the spectral shift of a galaxy results from both expansion and proper motion of the galaxy:

\[ V \sim \text{cz} = HD + v_{\text{p radial}} \]

Vp can be < 0

HD + Vp can be < 0 \implies \text{blue shift}

It happens if D not too large
Andromeda and the Milky Way are moving towards each other at a velocity $\sim 120 \text{ km/s}$. (expected collision in $\sim 4$ billion years)
At what distance does expansion act?

- Are we ourselves expanding?
- Is the solar system expanding?
- Is the Milky Way expanding?
- ...

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Exercice:
Let’s consider 2 bodies of mass « m » at a distance D. Above what distance D is their motion dominated by Hubble’s flow?

Equilibrium for \( D / Gmm/D^2 = ma = m\Delta V/dt = mHdD/dt = mHV = mH^2D \)

\[ D = (Gm/H^2)^{1/3} \]

For protons: \( D \sim 27 \text{ cm} \)
For MW type galaxies: \( D \sim 3 \text{ Mpc} \)

Consequence: expansion acts at scales > galaxy clusters. At smaller scales gravity wins.
If $V_p$ large => deviations from $V = H D$
If $D$ large => $V$ dominated by expansion
Blast of Giant Atom

By Donald H. Menzel
Harvard Observatory

OUT of a single nuclear event come all the stars and planets of the solar system. The enigmatic theory advanced by the German, Heisenberg, and later by Einstein, has turned the view of astronomers throughout the world upside down. It is an intellectual revolution that is giving birth to a new cosmology.

According to Einstein’s theory, all the visible universe can be understood as the remnant of a single gigantic event, which must have taken place billions of years ago. This theory suggests that the universe was born in a single instantaneous explosion, which is known as the Big Bang. According to this theory, the universe began as a tiny, dense, hot团, which then expanded and cooled over billions of years, eventually forming the stars and galaxies we see today.

The present writer, Donald H. Menzel, will explore the implications of this theory, and discuss the evidence that supports it. He will also examine the challenges and controversies that surround this revolutionary idea. This article was published in Popular Science in December 1932.

NB: Big Bang is not an explosion!
H is the inverse of a time

« Age of the universe » ~ \( 1/H \) (if H does not vary too much)
Measurements of $H$

Universe younger than the Earth!

Big bang models become standard

No known objet is older than the universe with $H \sim 50-100$
More recent Hubble diagram

Data used by Hubble
Quantities derived from « H »

\[ H = 67.8 \pm 0.9 \text{ km} / \text{s} / \text{Mpc} \text{ (Planck Mission)} \]

- « Age of the universe » \(1/H \sim 13.7 \text{ billion years}\)
- Hubble’s radius : \(c/H \sim 4.27 \text{ Gpc}\)
- 1915  GR  links geometry of space time and energy-matter content

- 1917  early times of physical cosmology with GR.
         A. Einstein – The static Universe

- 1922  A. Friedmann – First solutions of expanding/contracting Universes

- 1927  G. Lemaître  – Possibility of an expanding Universe; meets Hubble

Cosmology and GR ?

Assumption : the universe is filled of a homogeneous fluid (density/ pressure)

Most general metric :

$$ds^2 = c^2 dt^2 - R(t)^2 (dr^2 + r^2 d\Omega^2)$$

Let \( a(t) = \frac{R(t)}{R(t_0)} \) \( (a(t) \) is called scale factor) 

By convention \( t_0 = \text{now} \)

\( a(t) \) is the solution of a system of differential equations depending on the content of the universe

In 1917 Einstein searches for static solutions and introduces the cosmological constant.

He considered later that it was his biggest mistake to believe that adding a cosmological constant would make a stable static univers...
$$r \equiv ax$$

$a(t)$ is the scale factor
Friedmann – Lemaitre equations

\[
\left( \frac{\dot{a}}{a} \right)^2 + \frac{kc^2}{a^2} - \frac{\Lambda c^2}{3} = \frac{8\pi G}{3} \rho \\
2\left( \frac{\ddot{a}}{a} + \left( \frac{\dot{a}}{a} \right)^2 \right) + \frac{kc^2}{a^2} - \Lambda c^2 = -\frac{8\pi G}{c^2} p.
\]

Geometry $\Leftrightarrow$ Content

Full derivation in Slezak’s lectures
Classical solutions for $a(t)$
Main assumptions for a relativistic cosmology

• Postulates
  Laws of Physics are universal, in space and in time.
  The observable universe is representative of the universe as a whole

• Cosmological Principle :
  The Universe est isotropic, i.e. its aspect does not depend on the direction we observe.
  The Universe is spatially homogeneous, i.e. its general appearance does not depend on the position of the observer.

• The Earth does not occupy any privileged position in the universe (Copernican Principle)

Exemples:

Homogeneous non-isotropic  isotropic non-homogeneous
Cosmic time?

If the cosmological principle is not validated one cannot define a «mean» time that could be used to build a history of the universe common to any observer.
2 consequences of the Universe expansion that became observational pillars of Big-Bang models.

1. The Cosmic Microwave Background – CMB
2. Primordial nucleosynthesis
An old background noise ….
Antenna mounted in Holmdel in 1960 by the Bell Laboratories
Interpretation of the signal

Several assumptions were stated:
- The atmosphere?
- Human origin?
- The antenna itself?
- Astronomical sources?
- Pigeons?

⇒ The very high degree of isotropy of the signal led to the idea that it could come from the Universe itself. (a result published in 1965)

⇒ In the same journal an article from Dicke, Peebles, Roll & Wilkinson interprets the signal as a radiation emitted by the universe itself when it was hot and dense.

During 1966 the spectrum of this radiation is measured from 2.6 mm to 21 cm => consistent with a black body.
Meaning of a black body radiation

⇒ The universe went through a state in which matter and electromagnetic radiation were in thermodynamical equilibrium.

⇒ Favours models of expanding universes with a hot and dense phase.

⇒ NB: today, the universe is not anymore in thermodynamical equilibrium, and this since the end of matter-radiation coupling named « recombination ». 
Recombination

- When $T$ was $>> 3000K$ => ionised matter => electrons are free => electrons-photons interactions

- When $T$ became $< 3000K$ electrons are "captured" by nuclei, photons don’t interact with matter – decoupling => the Universe becomes transparent
Wien’s law: $\lambda_{\text{max}} \cdot T = \text{cste}$
CMB spectrum

Ground (>1965)

High atmosphere (1970 - 1980’s)

Space (>1990)

Difficult to detect because very isotropic: no differential measurements and therefore difficult to distinguish from a noise.
Cosmic Microwave Background spectrum

COBE Satellite – 1992
Best known black body
A. Penzias & R. Wilson in 1965 – Nobel Prize in 1978
The dipole reflects the Earth’s motion (\( \sim 600 \) km/s)
Once these anisotropies subtracted => very strong anisotropy = \( \frac{dT}{T} \sim 10^{-5} \)

Foreground anisotropies produced by the Milky Way

Map of the largest amplitude anisotropies detected by COBE (1992) on the whole celestial sphere.

The color code maps temperature variations
At recombination photons are emitted ~ at the same time

⇒ For us, observers, they form an image on a fictive sphere corresponding to the moment of recombination. It is the oldest «photonic» image of the universe.

We know that

\[ T(\text{ionisation}) = 3000K \]
\[ T(\text{now}) = 3K = T_0 \]

From the 2nd law of thermodynamics

\[ \frac{dV}{V} = -3 \frac{dT}{T} \]

Let \[ V = a^3 \]
\[ dT/T = -da/a \]

\[ T(t) = T_0/a(t) \] where \( a(t) \) is the scale factor

Knowing \( a(t) \) ⇒ the image of the CMB corresponds to an age of \(~380.000 \text{ years}\)
Evolution of CMB Temperature as a function of redshift

\[ \lambda_\text{o} / \lambda_e = a(0) / a(t) = 1 / a(t) \]
\[ z = (\lambda_\text{o} - \lambda_e) / \lambda_e \]
\[ 1 + z = 1 / a(t) \]
\[ T = T_0 (1 + z) \]
\[ z \text{ (CMB)} \sim 1000 \]
Is the Universe too isotropic? The problem of the horizon

- Size of the universe at decoupling
- Last Scattering Surface (CMB emission)

Angular size of a connected surface at decoupling $\sim 1.8$ degrés

How to explain isotropy on the whole sphere?

$\Rightarrow$ Inflation Theories (all regions would have been connected earlier in the history of the universe)
Primordial nucleosynthesis
Thermal history of the Universe

Opaque universe

$\text{380,000 years}$

Transparent universe

$t_P$  \hspace{1cm} $t_{\text{rec}}$

Limit of photonic observations

Hot and dense universe $\Rightarrow$ Nuclear physics

Creation of light atoms by nuclear reactions in the early universe $\Rightarrow$ primordial nucleosynthesis

The actors: George Gamow, Ralph Alpher, etc. – Series of articles en 1946 - 1948
The universe went through two main phases:

1. **Opaque universe** (up to 380,000 years):
   - Formation of protons & neutrons: +0.0001s
   - Limit of photonic observations

2. **Transparent universe** (after 380,000 years to ~500 millions years):
   - Hydrogen (1p): ~74%
   - Helium (2p, 2n): ~24%
   - Helium 3 (2p, 1n)
   - Deuterium (1p, 1n)

The observed composition of the universe indicates a significant presence of hydrogen and helium.
Deuterium abundance

Isotope of Hydrogene = 1p 1n

Deuterium is one of the less linked nuclei (2,2 MeV enough to separate its neutron – proton constituent) and do not resist to the typical temperatures of the inter stellar medium, where it is destroyed.

Can only be explained by the Big-Bang: a fast cooling allowed not to have it destroyed.
Abondances of light elements in the universe

Depends

- On the temperature (CMB) of the universe
- Relative density of baryons / photons
Very good consistency between observations and Big-Bang models (expanding universes)

- Receding galaxies following Hubble’s law \( V = H D \)
- Age of the universe and age of objects contained in the universe
- Existence of a diffuse radiation at 3K (CMB)
- Abundances of light elements in the universe
BUT ... the universe is not perfectly homogeneous!
Structures at all scales? Contradiction avec le principe cosmologique?

- ...

- us

- Planetary systems

- Stars cluster in galaxies

- Galaxies in galaxy clusters

- clusters in superclusters?

- Is there a scale above which we tend towards uniformity?