Einstein’s Universe

Relativity and the big bang

Cormac O’Raifeartaigh FRAS

Waterford Institute of Technology
75 years of DIAS

Founded in 1940 (de Valera)
Modelled on Princeton Research Institute (IAS)

Two schools

School of Theoretical Physics
School of Celtic Languages
Only pen and paper required

International expertise in physics

Erwin Schrödinger as first Director
Later followed by Heitler, Lanczos and Synge

Major centre for relativity, quantum physics
Overview

- **100 years of relativity**
  - *The special theory of relativity (1905)*
  - *The general theory of relativity (1915)*

- **General relativity and the universe**
  - *The expanding universe*

- **Astronomy and the universe**
  - *The recession of the galaxies*
  - *Models of the expanding universe*

- **The big bang model**
  - *Rival theories*
  - *Today’s big bang model of the universe*
Relativity

The principle of relativity

Laws of mechanics identical for observers in uniform motion
Non-accelerated motion

Galileo

Motion of ball in cabin of sailing ship
Impossible to deduce motion of ship

Application

Elizabeth I and the Irish Chieftains

Everyday experience

Cup of tea on train
Life on earth
Relativity in the 19th century

- **Electromagnetism**
  
  *Electricity and magnetism = electromagnetism*
  
  Speed of electromagnetic wave = speed of light

- Light = an electromagnetic wave
  
  *Travelling wave*
  
  *Changing electric and magnetic fields*

- **The electromagnetic spectrum**
  
  *From radio waves to X-rays*

- **Speed of light absolute?**
  
  *Fixed for all observers?*
  
  *Michelson-Morley experiment*
Einstein’s special theory of relativity

- **Two new principles (1905)**
  - Laws of physics the same for observers in uniform motion
  - Speed of light the same for observers in uniform motion

- **Implications**
  - Distance and time not absolute \( v = \frac{s}{t} \)
  - Experienced differently by bodies in motion

- **Predictions for high-speed bodies**
  - Length contraction; time dilation
  - Mass increase; equivalence of mass and energy \( E = mc^2 \)

- **Space + time = spacetime**
  - Space-time invariant (Minkowski)
Evidence for special relativity

- **Mass increase**
  
  *The experiments of Kaufmann and Bucherer*

\[ m' = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

- **Time dilation**
  
  *The long-lived muon*

\[ t' = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

- **Invariance of the speed of light**
  
  *Always measured as \( c \)*

- **Particle experiments at the LHC**

  *Maximum velocity = \( c \)*

  *Mass increase*

  *Particle creation*

\[ E = mc^2 \]
The general theory of relativity (1915)

- **General relativity**
  - Relativity and accelerated motion?
  - Relativity and gravity?

- **The principle of equivalence**
  - Cannot distinguish between gravity and acceleration

- **A new theory (1915)**
  - \( G_{\mu\nu} = -\kappa T_{\mu\nu} \)
  - Space-time distorted by mass
  - Gravity = curvature of space-time

- **Empirical evidence**
  - Orbit of Mercury
  - Bending of starlight by the sun (Eddington, 1919)
Evidence for general relativity

- Bending of distant light by stars
  *Gravitational lensing*

- Gravitational redshift
  *Shift in wavelength of light due to gravity*

- Gravitational time dilation
  *GPS corrections*

- Black holes
  \[ G_{\mu\nu} = -\kappa T_{\mu\nu} \]
  *Centre of galaxies*

- Gravitational waves
  *Hulse–Taylor binary system*
II Relativity and the universe

Apply general relativity to the cosmos (1917)
Ultimate test for new theory of gravity

Dynamic universe?
Expanding or contracting

Observation: static universe
Add new term to field equations
The cosmological constant $\lambda$

A static spherical universe
Closed universe with no boundaries
Cosmic radius and matter density defined by $\lambda$

\[
G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}
\]

Einstein’s universe
De Sitter’s universe (1917)

- Apply general relativity to the cosmos
  Alternative solution

\[ G_{\mu\nu} + \lambda g_{\mu\nu} = 0 \]

- ‘Empty’ universe
  Reasonable approximation

- Disliked by Einstein
  Conflict with Mach’s principle
  Beginning of Einstein’s dislike for cosmic constant

- Interest from astronomers
  Redshift prediction – Slipher effect?
  Static or non-static model? (Weyl 1923, Lemaître 1925)
Friedman’s universe

- Allow time-varying solutions (1922)
  - Assume positive spatial curvature
  - Universe of time-varying radius
    \[ G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu} \]

- Expanding or contracting universe
  - A universe evolves over time

- Badly received
  - Considered “suspicious” by Einstein
  - “To this a physical reality can hardly be ascribed”

- Negative spatial curvature (1924)
  - Cosmic evolution, geometry depends on matter content
III  Astronomy and the Universe

The Great Debate  (1900-1925)
Spiral nebulae = galaxies beyond Milky Way?

The Hooker telescope  (1917)
Edwin Hubble (1921)

The distances of the nebulae (1925)
Cepheid variables resolved in two nebulae
Leavitt’s period-luminosity relation

Spirals far beyond Milky Way
A universe of galaxies
The motion of the nebulae

- **The redshift of the nebulae**
  
  *V.M. Slipher (Lowell Observatory)*
  
  *Light from most nebulae redshifted (1915, 1917)*

- **Doppler effect**
  
  *Frequency of light depends on motion of source relative to observer*

- **Nebulae moving outward?**
  
  *Galaxies moving outward?*
The runaway galaxies (1929)

- A relation between redshift and distance for the galaxies?

- Combine 24 distances with redshifts

  Redshifts from Slipher: not acknowledged

- Linear relation: Hubble’s law (1929)
  \[ v = H_0 d \text{ with } H = 500 \text{ kms}^{-1}\text{Mpc}^{-1} \]

- Landmark result in astronomy

  Far-away galaxies rushing away
  at a speed proportional to distance

Why?
Lemaître’s universe (1927)

- **Expanding model of the cosmos from GR**
  *Similar to Friedman 1922 model*
  *Starts from static Einstein universe*

- **Recession of nebulae = expansion of space?**
  *Redshifts from Slipher, distances from Hubble*
  \[ H = 585 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

- **Ignored by community**
  *Belgian journal (in French)*
  *Rejected by Einstein: “Votre physique est abominable”*
  *Einstein not up-to-date with astronomy?*
The expanding universe (1930)

- **RAS meeting (1930)**
  
  *Eddington, de Sitter*
  
  If redshifts are velocities, and if effect is non-local
  Static cosmic models don’t match observations

- **Expanding universe?**
  
  *Hubble’s law = expansion of space?*
  
  \[ H = 500 \text{ km} s^{-1} \text{ Mpc}^{-1} \]

- **Friedman-Lemaître model circulated**
  
  *Time-varying radius*
  
  *Time-varying density of matter*
  
  Evolving universe
Models of the expanding universe (1930 -)

- **Eddington (1930, 31)**
  
  *On the instability of the Einstein universe*
  
  *Expansion caused by condensation?*

- **Tolman (1930, 31)**
  
  *On the behaviour of non-static models*
  
  *Expansion caused by annihilation of matter?*

- **de Sitter (1930, 31)**
  
  *Further remarks on the expanding universe*
  
  *Expanding universes of every flavour*

- **Einstein (1931, 32)**
  
  *Friedman-Einstein model*  \( \lambda = 0, k = 1 \)
  
  *Einstein-de Sitter model*  \( \lambda = 0, k = 0 \)

  *Occam’s razor?*

  *Evolving models*

  *No mention of origins*
The big bang model (1931)

- Expanding $U$ smaller in the past
- Rewind expanding model to early epochs
- Extremely dense, extremely hot
- Expanding and cooling ever since
- Explosive beginning at $R = 0$?

Later called ‘The big bang’
IV The ‘big bang’ model (1931)

- Infant $U$ concentrated in tiny volume
- Extremely dense, hot
- Expanding and cooling ever since

Where do the laws of physics come from?

Wrong age (Hubble constant)

Singularity problem
\[ \infty \text{ density, } \infty \text{ temp at } t = 0 \, ? \]
A new line of evidence

- Expert in nuclear physics (1940s)
  Student of Friedman

- How were the chemical elements formed?
  In the stars? Problems

- Elements formed in the big bang?
  Predicts $U = 75\%$ Hydrogen, $25\%$ Helium

- Agreement with observation
  Victory for big bang model

Heavier atoms formed in stars
A strange prediction

- Infant universe very hot indeed
- Dominated by radiation
- Still observable today?  
  *Low temp, microwave frequency*
- A fossil from the early universe
  *Released when atoms formed (300,000 yr)*

*No-one looked (1940s)*

Alpher, Gamow and Herman
Steady-state universe (1948)

- Alternative to big bang *(Fred Hoyle)*
- Expanding universe

**BUT**

- Continuous creation of matter?
- Unchanging universe
- No beginning, no age problem
- No assumptions about early epochs

*Very little matter needed*
Optical astronomy (1950s)
Amended timescale of expansion (Baade, Sandage)
Age problem removed

Radio-astronomy (1960s)
Galaxy distributions at different epochs
Cambridge 3C Survey (Ryle)

Cosmic microwave background (1965)
Low temperature, low frequency
Remnant of young, hot universe

End of steady-state theory
Cosmic background radiation

**CMB discovered accidentally**

- Universal signal (1965)
- Low frequency (microwave)
- Low temperature (3K)

*Echo of Big Bang!*

*Penzias and Wilson* (1965)
The big bang – evidence

1. The expansion of the $U$

2. The abundance of $H$ and $He$

3. The distribution of the galaxies

4. The cosmic microwave background

How did it start?
Modern measurements of the CMB

- Details of background radiation
- Full spectrum
- Comparison with theory
- Perturbations?
  
  - Ground telescopes
  - Balloon experiments
  - Satellite experiments

COBE satellite (1992)
COBE measurements of CMB

- Expected temperature
- Expected frequency
- Perfect blackbody spectrum

- Radiation very uniform
- Variation of 1 in $10^5$
- Seeds of galaxies?

Nobel Prize

COBE (1992)
The big bang model
Coda: Einstein’s 1931 model

- **Einstein’s first dynamic model of the cosmos**  
  Often cited, rarely read (not translated)

- **Adopts Friedman 1922 model**  
  Time-varying, closed universe: \( k = 1 \)  
  Cosmic constant redundant: set \( \lambda = 0 \)

- **Use Hubble to extract parameters**  
  Radius \( R \sim 10^8 \) lyr  
  Density of matter \( \rho \sim 10^{-26} \) g/cm\(^3\)

- **Timespan problem**  
  \( 10^{10} \) yr: conflict with astrophysics  
  Attributed to simplifying assumptions (homogeneity)
Einstein’s 1931 model revisited

- **First translation into English**
  
  *O’Raifeartaigh and McCann 2014*

- **Anomalies in calculations of radius and density**
  
  \[ R \sim 10^8 \text{ lyr} : \text{should be } 10^9 \text{ lyr} \]
  \[ \rho \sim 10^{-26} \text{ g/cm}^3 : \text{should be } 10^{-28} \text{ g/cm}^3 \]
  \[ t \sim 10^{10} \text{ yr} : \text{should be } 10^9 \text{ yr} \]

- **Source of error?**
  
  *Error in Hubble constant (Oxford blackboard)*
  \[ D^2 \sim 10^{-53} \text{ instead of } 10^{-55} \text{ cm}^{-2} \]

- **Not a cyclic model**
  
  “Model fails at \( P = 0 \)”
  
  *Contrary to what is often stated*
Bonus: Einstein’s steady-state model

Unpublished manuscript
Archived as draft of Einstein’s 1931 model
Similar title, opening

Something different
Cosmological constant $\lambda$
“Constant matter density determines expansion”

Steady-state model
Continuous formation of matter from vacuum
Fatal flaw; abandoned

Anticipates Hoyle’s theory
Abandoned model

- **de Sitter line element**
  - Correct geometry

- **Simultaneous equations**
  - Error in derivation
  - Null solution

- **Einstein’s crossroads**
  - Realised problem on revision
  - Declined to amend model

- **Evolving models**
  - Less contrived and set $\lambda = 0$
Einstein’s lost theory uncovered

Physicist explored the idea of a steady-state Universe in 1931.

Davide Castelvecchi

24 February 2014

New Discovery Reveals Einstein Tried To Devise A Steady State Model Of The Universe

Almost 20 years before the late Fred Hoyle and his colleagues devised the Steady State Theory, Albert Einstein toyed with a similar idea: that the universe was eternal, expanding outward with a consistent input of spontaneously generating matter.

An Irish physicist came across the paper last year and could hardly believe the model of the universe very different to today's Big Bang Theory.

The manuscript, which hadn't been referred to by scientists for decades, provided evidence that Einstein had toyed with the idea of a steady-state universe.
Einstein’s universe: conclusions

- **Cosmology = test for general relativity**
  - Introduces $\lambda$-term to the field equations

- **Embraces dynamic cosmology**
  - New evidence – new models
  - Steady-state vs evolving universe
  - Evolving models simpler: remove $\lambda$-term

- **The evolving universe**
  - Extract observational parameters
  - Timespan problem attributed to simplifying assumptions

- **No discussion of origins**
  - Wary of extrapolations

- Hubble constant revised

- Cosmic microwave background
  - Homogeneous, flat universe
100 years of general relativity

Published Nov. 25th 1915

From Swiss patent office to Berlin

A new theory of gravity

Gravity = curvature of spacetime

Predictions supported by experiment

Bending of light by a star
Expanding universe
Gravitational time dilation (GPS)

One more test

Gravitational waves

Mike Cruise, Nov 25th St Patrick’s College, Drumcondra
Über das sogenannte kosmologische Problem.

Archival Call Number: 1-115
Begin Date: 1932-09-01
End Date: 1932-09-30
Main Author: Einstein, Albert (Author)
Other Persons: Mayer, Walter (Author)
Language: German
Archival Location: Albert Einstein Archives, The Hebrew University of Jerusalem, Israel
Number of Pages: 11

Document Type: Autograph Draft of Document (ADOft)
Einstein’s steady-state model and cosmology today

- Dark energy (1998)
  - Accelerated expansion (observation)
  - Positive cosmological constant

- Einstein’s dark energy
  “The conservation law is preserved in that, by setting the $\lambda$-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1).”

- Cosmic inflation
  - Inflationary models use de Sitter metric
  - Used in all steady-state models
  - Flat curvature, constant rate of matter creation
  - Different time-frame!
Einstein’s steady-state model: key quotes

**New solution**

“In what follows, I wish to draw attention to a solution to equation (1) that can account for Hubbel’s facts, and in which the density is constant over time”

**Matter creation**

“If one considers a physically bounded volume, particles of matter will be continually leaving it. For the density to remain constant, new particles of matter must be continually formed within that volume from space “

**Dark energy**

“The conservation law is preserved in that, by setting the $\lambda$-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1).”
Einstein-de Sitter model (1932)

**Curvature not a given in dynamic models**

*Not observed empirically*

*Remove spatial curvature (Occam’s razor)*

\[
d s^2 = -R^2(dx^2 + dy^2 + dz^2) + c^2dt^2
\]

**Simplest Friedman model**

*Time-varying universe with \( \lambda = 0, k = 0 \)*

*Important hypothetical case: critical universe*

*Critical density: \( \rho = 10^{-28} \text{ g/cm}^3 \)*

**Becomes standard model**

*Despite high density of matter*

*Despite age problem*

*Time evolution not considered in paper – see title*
Einstein-de Sitter model revisited

- Einstein’s cosmology review of 1933
  - Review of dynamic models from first principles
  - Culminates in Einstein-de Sitter model
  - Cosmic constant banished
  - Possibility of flat geometry

- Parameters extracted
  - Critical density of $10^{-28}$ g/cm$^3$: reasonable
  - Timespan of $10^{10}$ years: conflict with astrophysics
  - Attributed to simplifications (incorrect estimate)

- Published in 1933!
  - French book; small print run
  - Intended for scientific journal; not submitted
  - Significant paper
Einstein’s steady-state theory: a significant find?

- New perspective on steady-state theory (1950s)
  Logical possibility: not a crank theory

- Insight into scientific progress
  Evolution of successful theories
  No Kuhnian paradigm shift to ‘big bang’ model
  Slow dawning

- Insight into Einstein’s philosophy
  Simple solution?
  Discards model rather than introduce new term to GFE
  Occam’s razor approach

- Links with modern cosmology
  Dark energy, cosmic inflation

Paradigm shift or slow dawning?
Explanation for runaway galaxies?

**Newton**

• Gravity pulls in not out

• Space is fixed

• Time has no beginning

*How can galaxies be receding? What is pushing out?*
Results: publications

- **Einstein’s 1931 model**
  

- **Einstein’s steady-state manuscript**


- **Einstein-de Sitter model**


- **Review paper: conclusions**
Einstein’s steady-state theory: an abandoned model of the cosmos

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Received 1st February 2014 / Received in final form: 12 May 2014

Abstract: We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a ‘steady-state’ model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein was considering a steady-state model in which the mass density of matter in an expanding universe is maintained constant by the continuous formation of matter from empty space. This model is very different to previous...
Taking $T_{44} = \rho c^2$ (all other components zero) in the \textit{time} component of equation (1) we obtain \( \left( R_{44} - \frac{1}{2} g_{44} R \right) - \lambda g_{44} = \kappa \rho c^2 \).

This gives on analysis \(-3 \alpha^2/4 + 3 \alpha^2/2 - \lambda c^2 = \kappa \rho c^2\) the second of Einstein’s simultaneous equations.

From the \textit{spatial} component of equation (1), we obtain \( \left( R_{ii} - \frac{1}{2} g_{ii} R \right) - \lambda g_{ii} = 0 \).

This gives on analysis \(3 \alpha^2/4 - 3 \alpha^2/2 + \lambda c^2 = 0\) for the first of the simultaneous equations.

It is plausible that Einstein made a sign error here, initially getting \(3 \alpha^2/4 + 3 \alpha^2/2 + \lambda c^2 = 0\) for this equation. (W. Nahm)
Einstein’s steady-state model and cosmology today

- **Accelerated expansion (1998)**
  - Supernova measurements
  - Dark energy – positive cosmological constant

- **Einstein’s dark energy**
  - “The conservation law is preserved in that, by setting the \( \lambda \)-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1).”
  - Anticipates positive cosmological constant

- **De Sitter line element**
  - \( ds^2 = -e^{\alpha t} (dx_1^2 + dx_2^2 + dx_3^2) + c^2 dt^2 \ldots \)
  - Necessary for all steady-state models
  - Identical to inflationary models (different time-frame)
The steady-state universe (1948)

- Expanding but unchanging universe
  
  *Hoyle, Bondi and Gold (1948)*
  
  Disliked speculation about physics of early epochs
  
  Perfect cosmological principle?

- Continuous creation of matter
  
  Very little matter required
  
  No beginning, no age paradox

- Replace $\lambda$ with creation term (Hoyle)
  
  $$ G_{\mu\nu} + C_{\mu\nu} = -kT_{\mu\nu} $$

- Improved version (1962)
  
  $$ G_{\mu\nu} + \lambda g_{\mu\nu} = kT(C_{\mu} + C_{\nu}) $$
Conclusions

**Cosmology – a testing ground for general relativity?**

- Assumptions; space-time = space + time
- Homogeneity and isotropy
- Static universe

**Dynamic cosmology**

- Steady-state universe?
- Evolving models less contrived

**Evolving models**

- Timespan problem: attributed to assumptions
- Origins puzzle: ignored

**Verdict**

- More data needed