Einstein, the expanding universe and the big bang

Paradigm shift or slow dawning?

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Astronomy Ireland, Dublin, 13/01/14
A drama in three acts?

- **A brief history of observation (1912-1931)**
  - The redshifts of the spiral nebulae (Slipher)
  - The distances to the nebulae (Hubble)
  - The Hubble graph of 1929

- **A brief history of theory (1915-1931)**
  - The static universes of Einstein and de Sitter
  - The dynamic universes of Friedman and Lemaître

- **An expanding universe? (1930)**
  - Explorations of a dynamic universe (1927-35)
  - Slow acceptance by physics community (1935-65)

- **A slow dawning? Acts IV and V**

Many other actors
I. The starry nebulae

- Observed by Marius (1614), Halley, Messier

- Island universes? Kant, Laplace (1755-96)
  Collections of stars at immense distance?
  Are stars born in the nebulae?

- Wilhem Herschel
  36-inch reflecting telescope
  Catalogue of a thousand (1786)

- Earl of Rosse
  72-inch reflecting telescope (1845)
  Some nebulae have spiral structure, stars

Problem of resolution, distance
The spectra of the nebulae

- **Photography and spectroscopy (19th cent)**
  *Emission and absorption lines of celestial objects*

- **Composition of the stars and planetary nebulae**
  *William Huggins*

- **Radial motion of the stars**
  *Doppler effect*
  *William Campbell*

- **Spectroscopy of spiral nebulae?**
  *Information on evolution of solar system*

- **Difficult to resolve**

\[ \frac{\Delta \lambda}{\lambda} = \frac{v}{c} \]
Slipher and the spiral nebulae

- **Analyse light of the spiral nebulae? (1909)**
  *Lowell Observatory; evolving solar system?*

- **Slipher reluctant**
  *24-inch refractor: larger telescopes failed*

- **Experiments with spectrograph camera**
  *Good results with fast camera lens*

- **Clear spectrum for Andromeda nebula (1912)**
  *Significantly blue-shifted; approaching at 300 km/s?*

- **Many spiral nebulae red-shifted (1915)**
  *Standing ovation (AAS, 1914)*
  *Attended by Hubble*
Redshifts of the nebulae

• **Spectra of 25 spirals (1917)**
  Large outward velocities
  Some receding at 1000 km/s

• **Much faster than stars**
  Gravitationally bound by MW?

• **Island universe debate**
  “Island universe hypothesis gains favour”

• **Faintest spectra most redshifted**
  Evidence of expansion? (retrospective)

• **41 redshifts by 1922**
  Published by Eddington, Strömberg

\[ \Delta \lambda / \lambda = v / c \]

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II  General relativity (1915)

- **Space+time = space-time**
  
  *Spacetime dynamic (1905)*

- **Spacetime distorted by mass**
  
  *Distortion causes other mass to move*

- **Gravity = curvature of space-time**
  
  \[ G_{\mu\nu} = \nabla T_{\mu\nu} \]

- **Dyson/Eddington expeditions (1919)**
  
  *Measure bending of light?*
  
  *Successful result*
  
  *General relativity well-known*
Apply relativity to the cosmos (1917)

**Einstein model (1917)**
- Homogenous fluid of uniform density
- Equations predict dynamic universe
- No evidence for such a universe
- Add cosmic constant – ‘static’
- Closed curvature, finite radius

\[ G_{\mu \nu} + \lambda g_{\mu \nu} = \frac{8\pi G}{c^4} T_{\mu \nu} \]

**De Sitter (1917)**
- ‘Empty’ universe
- Apparently static (co-ordinate system)
- Cosmic constant determined by curvature of space
- Redshifts due to time dilation/matter

*Disliked by Einstein: Mach’s principle*
Redshifts and the de Sitter model

**Karl Wirtz** (1922,24)

*Redshifts of nebulae increasing with distance*

*Dispersal effect? $v = 2200 - 1200 \log (Dm)$*

**Ludwik Silberstein** (1924)

*Relation between redshifts, distance, curvature*

$\Delta \lambda/\lambda = +/- r/R$ (global clusters)

**Knut Lundmark** (1924,25)

*Velocity against distance; clusters, nebulae*

**Gustav Strömberg** (1925)

*Vel/dist relation for globular clusters, nebulae?
Friedmann universes (1922, 24)

- Allow time-varying solutions to the field equations
  - Allow cosmic constant
  - All possible universes

- Geometry, evolution depends on matter
  - Positive curvature (1922)
  - Hyperbolic curvature (1924)

- Hypothetical models (Zf. Ph.)
  - To be decided by astronomy

- Disliked by Einstein
  - Correction and retraction

Ignored by community
The distances of the nebulae (1925,26)

- **Hooker telescope (Mt Wilson)**
  100-inch reflector (1917)

- **Edwin Hubble (1921)**
  Ambitious and dedicated astronomer

- **Resolved Cepheid stars in nebulae (1925)**
  Leavitt’s period-luminosity relation
  Standard candle

- **Spirals beyond Milky Way**
  Nebulae = galaxies
  Beginning of end of ‘Great Debate’
Is there a redshift/distance relation for galaxies?

Motivation: establishing distance to the galaxies

Combine 24 nebular distances with redshifts

Redshifts from Slipher: not acknowledged

Approx linear relation (Hubble, 1929)

Some errors (Peacock)
Most important point not shown

What do the redshifts mean?

Reference to de Sitter universe

\[ H = 585 \text{ km s}^{-1} \text{ Mpc}^{-1} \]
III  An expanding universe? (1930-)

• RAS meeting  (1930)
  Eddington, de Sitter
  Distances and redshifts of the nebulae
  Einstein, de Sitter models don’t fit

• Lemaître letter
  Reminds Eddington of his 1927 model
  Eddington, de Sitter impressed

• Expansion of space-time metric?
  Considered by many theoreticians
  If redshifts are velocities (Zwicky)
  If effect is non-local
  Not accepted by astronomers (Hubble)
Lemaître’s universe (1927)

- **Redshifts of galaxies** = cosmic expansion?
  
  Rate of expansion from ave. distance and redshift
  
  \[ H = 585 \text{ km/s/Mpc} \]

- **Matter-filled \(U\) of increasing radius**
  
  de Sitter model not static (1925)
  
  New evolving solution: Einstein → deS

- **No beginning: indefinite age**
  
  Starts from Einstein universe at \( t = -\infty \)

- **Rejected by Einstein**
  
  An idea whose time had not yet come

Fr Georges Lemaître

Not an empirical law
Edited in 1931 translation
Dynamic models of the cosmos (1931,32)

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

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

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

• **Einstein (1931, 32)**
  *Friedmann-Einstein model* $\lambda = 0, k = 1$
  *Einstein-deSitter model* $\lambda = 0, k = 0$
  *If redshifts represent velocities…*
  *If effect is non-local …*
Einstein’s 1931 model \((F-E)\)

- Instability of static universe
  
  Eddington’s paper

- Hubble’s observations
  
  Expanding cosmos
  
  Remove cosmic constant?

- Adopt Friedmann 1922 analysis
  
  Time-varying universe, \(k=1, \lambda=0\)

- Age and singularity problems
  
  Attributes to limitations of theory
Einstein’s 1931 model (F-E)

- **Numerical estimates of radius and density**
  
  *Use Hubble parameter*
  
  \[ P \quad 10^8 \text{ light-years, } \rho \quad 10^{-26} \text{ g/cm}^3 \]

- **Calculations problematic**
  
  \[ H_0 \quad 500 \text{ km s}^{-1} \text{ Mpc}^{-1} : D^2 \quad 10^{-55} \text{ cm}^2 \]

- **Age estimate problematic**
  
  Age from Friedmann

- **Not a periodic solution**
  
  “Model fails at \( P = 0 \)”

\[
D = \frac{1}{c} \frac{dl}{dt} = \frac{1}{c} \frac{dP}{d\tau} \\
D^2 = \frac{1}{P^2} \frac{P_0 - P}{P} \sim \frac{1}{P^2} \quad (1a) \\
D^2 \sim \frac{K \rho_0}{3} \quad \left( \frac{P_0 - P}{P} \right) \sim \frac{1}{\rho_0} \quad (2a) \\
D^2 \sim 10^{-55} \\
\rho \sim 10^{-26} \\
P_0 \sim 10^8 \text{ L}_{\odot} \text{ Y} \\
t \sim 10^{10} (10^{11}) \text{ Y}
\]
Einstein-deSitter model (1932)

- **Remove curvature**
  
  *Not known*  
  *(Occam’s razor)*

- **Adopt Friedmann analysis**
  
  *Time-varying universe with $k = 0, \lambda = 0$*
  
  *Critical universe*

- **Calculate critical density**
  
  $10^{-28}$ g/cm$^3$: agrees with astrophysics

- **Well-known model**
  
  *Despite age problem*
Models: observational parameters needed

- **Spatial curvature** \( k = -1, 0, 1? \)
- **Cosmic constant** \( \lambda = 0? \)
- **Deacceleration** \( q_0 = -\) 
- **Density of matter** \( \rho < \rho_{\text{crit}}? \)
- **Timespan** \( \tau = 10^{10} \text{ yr}\) 
- **Hubble constant** \( = 500 \text{ kms}^{-1}\text{Mpc}^{-1}? \)

**What do redshifts represent?**
**Is expansion a local effect?**

*Hubble and Tolman 1935*
The formation of galaxies

- **Growth in static medium**
  
  *Natural fluctuations in density*
  
  *Exponential growth by gravitational collapse*
  
  \[ \lambda_j = c_s / (G \rho_0 \pi)^{1/2} \]

- **Growth in expanding medium**
  
  *Lemaître 1934, Tolman 1935*
  
  *Linear growth of density perturbations*
  
  \[ \delta \rho / \rho \propto R \]

- **Structure not from density fluctuations?**
  
  *New mechanism needed*
  
  *Eddington-Lemaître model?*
An origin for the universe?

- **Rewind Hubble graph**
  
  $U$ smaller in the past

- **Extremely dense, extremely hot**
  
  Expanding and cooling since
  Evolving universe

- **Age problem**
  
  Younger than stars?

- **Singularity problem**
  
  Breakdown of theory
  $\infty$ density, $\infty$ temp at $t = 0$ ?

*The big bang*
Lemaître’s hesitating universe (1931-34)

- **Primeval atom**
  *Explosive expansion from radioactive decay*

- **Expansion slows down**
  *Positive cosmic constant*
  *Energy of vacuum; stagnation*

- **Indefinite timespan**
  *No age problem*
  *Formation of structure?*

- **Accelerated expansion**
  *de Sitter universe at large t*

*Cosmic rays = radiation from early universe?*
IV Paradigm shift or slow dawning?

- **Hubble/Slipher**  
  *Empirical law for nebulae*

- **Friedmann**  
  *Time-varying solutions*

- **Lemaître**  
  *Theory and observation*

Obs: Parsons, Huggins, Leavitt, Shapley  
Models I: Einstein, de Sitter, Weyl, Lanczos, Robertson  
Models II: Einstein, de Sitter, Eddington, Tolman, Robertson

*Slow emergence of theory and evidence*  
*Slow acceptance: no upsurge of interest 1935-65*
IV Slow acceptance: 1940-60

- **Hot big bang** (1940s)
  - Nucleosynthesis in the infant universe?
  - Background radiation from early universe?

- **Little interest from community**
  - No interest from Lemaître, Einstein
  - No search for the cosmic radiation

- **Steady-state universe** (1948)
  - Continuous creation of matter from vacuum
  - No age or singularity problems

- **Later ruled out by experiment**
  - Radio-galaxy counts (long investigation)
  - Cosmic microwave background (Penzias and Wilson)
Cosmic background radiation

- **Search for radio signals**
  
  *Large, sensitive receiver*

- **Universal signal (1965)**
  
  *From every direction*

- **Low frequency (microwave)**
  
  *Low temperature (3K)*

- **Echo of big bang**
  
  *Radiation from early universe*

  *BB model goes mainstream*
Paradigm shift or slow dawning?

**Revolutionary v normal science**

*Normal science interspersed by revolutions*

**The paradigm shift**

*Change of worldview*

*Social factors important*

**Incommensurability**

*New worldview incommensurate with old*

*Exp U:慢 exploration of theory and observation*

*Slow acceptance of new paradigm (1960s)*
Coda: Einstein's steady-state model

- **Non-static line element (1930)**

- **Age problem**
  Conflict with stellar ages

- **Non-evolving universe**
  Constant matter density
  Continuous creation of matter
  Associated with $\lambda$; energy of space

- **Not published**
  No creation term: null solution
V Cosmology today

- **Satellite measurements of CMB**
  
  *No interference from atmosphere*

- **Expected temperature**
  
  *Expected frequency*

- **Full spectrum**
  
  *Perfect blackbody spectrum*

- **Perturbations**
  
  *Variation of 1 in $10^5$*
Planck Satellite (ESA): Results

COBE

WMAP

Planck
1. Improved sensitivity
\[ \frac{\Delta T}{T} \approx 1 \times 10^{-6} \]

2. Full spectrum of \( T \) anisotropy
   - New acoustic peaks: scale invariance?
   - Accurate values for \( \Omega_\Lambda, \Omega_M \)

3. Gravitational lensing
   - Remove degeneracies

4. Polarization measurements
   - \( E \)-modes: fluctuations
   - \( B \)-modes: gravity waves?
Planck results (2013)

1. **New Hubble constant**
   
   \[ H_0 = 67.3 \pm 1.2 \text{ km/s/Mpc} \]
   
   Age = 13.8 billion yr
   
   No age conflict with astrophysics

2. **Curvature: flat**
   
   \[ \Omega_k = -0.0005 \pm 0.07 \]

3. **Positive cosmic constant**
   
   \[ \Omega_\Lambda = 68\% \]

4. **New mass/energy parameters**
   
   \[ \Omega_{DM} = 27\%, \quad \Omega_{OM} = 4.9\% \]
Planck Results

1. Power spectrum
   Not scale invariant \( n_s = 0.96 \)

2. Compatible with inflation
   Simple ‘slow-roll’ models
   Higgs-type field?

3. Complex inflation out
   Double field out
   Hybrid models out
   Cyclic models out
The big bang model - questions

- Nature of dark energy?
  
  Role in BB?

- Nature of dark matter?
  
  Particle experiments?

- Which model of inflation?
  
  The multiverse?

- The singularity problem
  
  What banged?
  What does time zero mean?

The case is never closed
Tolman’s annihilation of matter

- **Non-static line element (1930)**
  
  *Einstein, de Sitter models ruled out*
  
  

- **Cause of cosmic expansion?**
  
  *General evolutionary process*
  
  *Transformation of matter into radiation*
  

- **Rate of transformation**
  
  *From Hubble’s law and from stellar physics*
  

- **Influenced Einstein**
  
  *Steady-state model*

\[ k = 5\times 10^{-10} \text{ yr}^{-1} \]