20th century cosmology

- **1920s – 1990s (from Friedmann to Freedman)**
  - **theoretical technology available, but no data**
  - **20th century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
    - Discovery of the CMB 1965
    - Inflation 1981
    - CMB anisotropies: COBE ~1990

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  - **20th century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
      - understanding of stellar structure and evolution
      - beginnings of quantitative predictions in cosmology
        - birth of the Big Bang and Steady State models
      - beginnings of non-optical astronomy
        - radio astronomy (1940s), satellites (1957 on)

State of Play, 1940

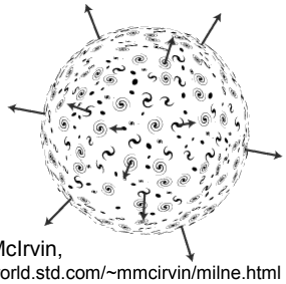
- **Hydrogen fusion finally understood**
  - **pp chain, Bethe and Crichton, 1938**
  - **CNO cycle, Bethe, 1939**
- **Hubble constant still ~500 km/s/Mpc**
  - **Hubble time ~2 Gyr, recognised as problem**
- **Most cosmological papers basically playing with the maths**
  - **not enough data to produce useful constraints**
  - **different theories owe more to differences in philosophy than anything else**

Cosmological models

- **Theories of the 1930s**
  - **general relativistic cosmologies**
    - Friedmann, Lemaître, Robertson
  - **"kinematic cosmology"**
    - Milne
      - special but *not* general relativity
      - finite "bubble" of galaxies expanding into pre-existing empty space
- **Theories of the 1940s**
  - **Hot Big Bang**
    - George Gamow, Ralph Alpher, Robert Herman
      - driven by nuclear physics
      - main prediction not tested for ~20 years!
  - **Steady State**
    - Fred Hoyle, Herman Bondi, Thomas Gold
      - driven by philosophy
      - produced unambiguous predictions

Milne cosmology

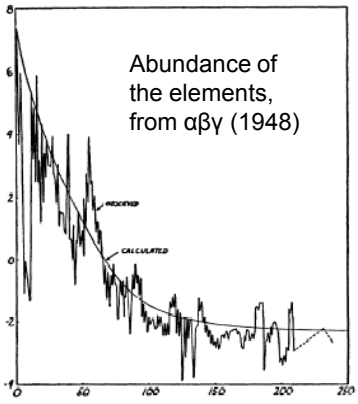
- **Galaxies are created at one point in a flat spacetime**
- **Galaxies behave as massless test particles**
  - **then "trivially" get $v = H_0 d$ (faster particles move further)**
- **Special relativity holds**
  - **Lorentz contraction lets us have infinitely many galaxies (almost all right at the edge of our expanding bubble)**
- **No special locations**
  - **Milne was the first to state this "Cosmological [or Copernican] Principle"**
- **This is essentially just the $\Omega = 0$, $k = -1$ "curvature only" model**
  - **(in slightly odd coordinates)**



Matt McIrvin,
http://world.std.com/~mmcirvin/milne.html

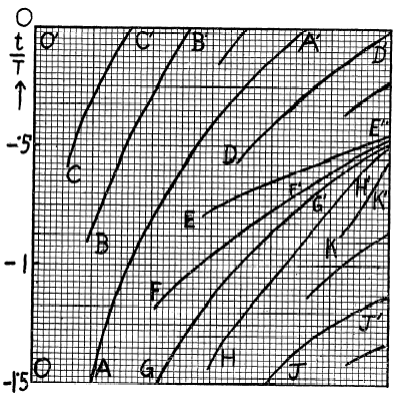
Hot Big Bang

- **Principal idea: assume initial ultradense state is hot (originally, hot neutron gas)**
  - **this is not trivial: original "big bang" models (Lemaître) had a cold big bang**
  - **generate heavy elements by combining neutrons**
    - this is wrong
    - no stable isotopes with mass 5 or 8
    - heavy element content of universe not uniform
  - **expect relic blackbody radiation**
    - hot dense initial state generates thermal spectrum
    - subsequent expansion redshifts it
  - **age of universe $\leq 1/H_0$**
    - awkward at the time, because H_0 high



Steady State

- **Principal idea: "Perfect Cosmological Principle"**
  - **we are located neither at a special place in space nor at a special time**
    - hence large-scale appearance of universe is always the same
      - same density
      - same Hubble parameter
      - infinite age
    - implication: matter must be created as universe expands
      - creation rate is very small, so essentially unobservable
  - **invented simultaneously by Hoyle and by Bondi & Gold**
    - critical point: very constrained, therefore predictive, model

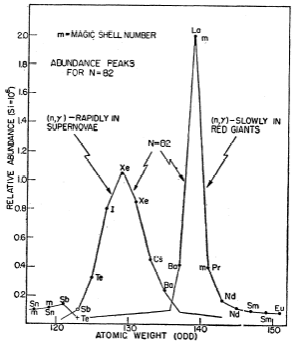


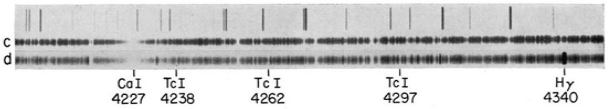
galaxy positions over time, from Bondi & Gold 1948

Nucleosynthesis

- **Modern theory of stellar nucleo-synthesis developed through 1950s**
  - **technetium seen in red giant spectra**
  - **heavy element abundance inversely correlated with age**
- **clearly superior to αβγ theory for all but the lightest nuclides**
  - **helium abundance not very well known at this time**
  - **suggested sites of deuterium production**
    - atmospheres
    - nebulae
  - **light elements not a smoking gun**

B^{2}FH, 1957





technetium lines in R Andromedae, Paul Merrill

State of Play, 1960

- **Big Bang cosmology**
  - **model for nucleosynthesis largely disproved**
    - stellar nucleosynthesis appears to work well
    - inverse correlation with age, existence of unstable nuclei
  - **prediction of cosmic background largely forgotten!**
  - **quantitative predictions difficult because of free parameters**
    - not only H, Ω, k, but also evolution, inhomogeneity
- **Steady State cosmology**
  - **assumes all nucleosynthesis stellar**
    - helium, lithium, deuterium possible but not definite problems
  - **requires new physics**
    - continuous creation of matter (not observable!)
  - **extremely highly constrained**
    - no evolution, no inhomogeneities
  - **therefore provides reliable predictions**

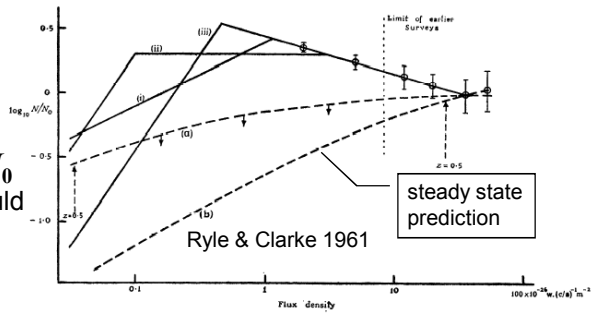
observational cosmologists can aim to test Steady State model

The Steady State model

- **H always constant, so $\mathrm{d}a/\mathrm{d}t = H_0 a$ or $a \propto \exp(H_0 t)$**
- **ρ always constant, so must have M/V = constant**
  - **therefore $\mathrm{d}M/\mathrm{d}t = \rho\, \mathrm{d}V/\mathrm{d}t = 3\rho H_0 V$**
  - **for a critically dense universe with H_0 = 72 km/s/Mpc this gives a creation rate of 6.8×10^{-44} kg m^{-3} s^{-1}**
    - about one hydrogen atom per cubic kilometre per year
    - this is obviously not detectable by reasonable technology!
  - **number density of any extragalactic standard candle should be constant**
    - therefore at z<<1 number brighter than flux f should be $\propto f^{-3/2}$
      - at higher z need to correct for redshift and curvature
      - requires understanding of source spectrum

Testing the Steady State Model

- **Radio galaxy source counts, early 1960s**
  - **excess of faint sources**
  - **actually not conclusive evidence, since most sources unidentified (population of faint Galactic sources would explain effect)**
- **Galaxy ages**
  - **should see some galaxies older than $1/H_0$**
    - but they should be very rare

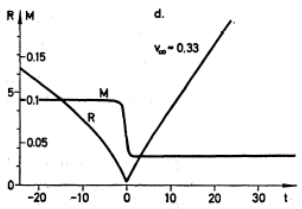


Alternative models

- **Cosmology ~1960 was not simply Big Bang vs Steady State**
  - **little data, therefore much room for alternative models**
  - **motivation generally philosophy rather than data**
- **Mach's principle**
  - **many statements, but basically the argument that accelerating (especially, rotating) frames are determined to be so with reference to the matter content of the Universe as a whole**
    - influential in development of General Relativity (which doesn't satisfy it)
    - satisfying it in expanding universe requires varying *G*
- **Particle physics**
  - **apparent matter-antimatter symmetry of physical laws**
    - why should universe be matter only, not matter-antimatter symmetric?

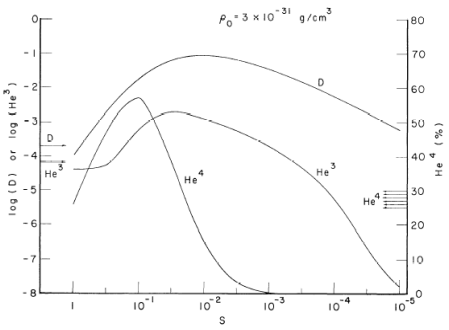
Plasma universe

- **Principles: matter-antimatter symmetry, no new laws of physics**
  - **Klein & Alfvén (1962, 1965)**
- **Initial state: dilute plasma (matter-antimatter symmetric)**
  - **collapses under gravity**
  - **at some point radiation pressure converts collapse to expansion**
  - **magnetic fields induce separation of matter and antimatter**
- **Problem:**
  - **size of "metagalaxy" limited by requirement that it not form black hole**
    - visible universe has an edge
    - expect anisotropy



Brans-Dicke cosmology

- **Alternative relativistic theory of gravity**
  - **gravitational force generated by scalar field** $\phi = \frac{4+2\omega}{3+2\omega}\frac{1}{G}$
  - **ω is a constant > 5**
    - GR recovered if $\omega = \infty$
    - neither ϕ nor G constant
- **Problems**
  - **experimental bounds on variation of *G***
  - **model tends not to make any helium!**
- **Recently resurfaced in string theories**



C. Greenstein, 1968

Triumph of the Hot Big Bang

- **State of play in early 1960s**
  - **main models: Hot Big Bang, Steady State**
  - **minor model: Brans-Dicke cosmology**
  - **radio source counts disfavour steady state**
    - but situation unclear because faint sources unidentified
- **State of play in late 1960s**
  - **Hot Big Bang rules, Steady State dead, Brans-Dicke fairly dead**
- **Mid-1960s saw critical advance in available data**
  - **discovery of microwave background**