Origin of the Universe. Geology Journal Club, Feb 1972.

Most of what I have to say is probably wrong.

Slide: "Age of the Universe" versus time. Log Age versus date.

1658 Archbishop Ussher. Biblical ages summed → Universe was created on Sunday, 23rd October, 4004 B.C.

1870 Lord Kelvin. ~ 40 million years, for age of Earth. If stars radiate by gravitational collapse, releasing gravitational potential energy, their lifetimes similar.

1930 Early radioactive dating of rocks → 2 billion years
Expansion time of Universe → 2 billion years.

1971 December. Latest unpublished revision of the Hubble expansion time → 20 billion years.

Geological age estimates have changed by ~2 in 40 years
Astronomical " " ~10 in same period, and are now much longer than geological estimates. Thus the Universe is comfortably older than the Earth! I feel it is unwise to suppose that this graph will now level off.

Slide: Astronomical method. (Peanuts & 365 stars).

Observe and interpret using local physics.
Postulate of simplicity until forced to complexity.

Slide: Pogo

Concepts of time-scale and origin have evolved with concept of "largest physical system". What do we mean by "the Universe"?

Astronomy texts at turn of 19th Century → flattened disc of stars (the Milky Way)
$\sim 10^{11}$ stars.
~ 100,000 l.y. across.

Beyond it? Boo all (except for philosophical speculations of Kant, which were almost entirely correct).

Now aware that this system is just one of literally billions of galaxies. The "Universe" of a 19th Century astronomer represents ~ 10^{-15} of the Universe I describe tonight.

Slide of M31. Nearest galactic neighbour, our big brother. 300 billion stars, 2 million l.y. away. As in our galaxy, spiral pattern containing many hot blue stars occupies disc distribution, nuclear bulge is full of highly evolved red giant stars of much greater mean age. This galaxy and ours are members of a "Local Group" of ~ 20 galaxies.

Slide of NGC 7331. Spiral arms rich in dust, heavy-element material, mostly carbon grains.

Slide of Coma Cluster Basic building-blocks of Universe are clusters of galaxies, groups of hundreds or thousands of galaxies measuring up to 10's of millions of l.y. across. Clusters frequently dominated by bright giant elliptical galaxies (D galaxies), which emit ~ 10^{37}-10^{38} watts or ~ $10^{11} L_\odot$, contain ~ up to $10^{12} M_\odot$

These giant galaxies are a powerful cosmological probe-tool, for they can be recognised at very great distances. Many are also radio emitters and can be picked out by use of radio telescopes, more readily than through optical surveys.

Slide of Hercules Cluster Profusion of galactic types.

Hydra Cluster Galaxies near the limit of detectability. About 1.6 billion l.y. away. Light that made this photograph almost certainly older than the Earth.

Distribution on sky — Homogeneous and isotropic on scales larger than about 200 million l.y. No strong evidence for further superstructure in Universe.

Distance indicators

Assume objects in other galaxies have similar light output to those in our own. For large distances, assume that complete galaxies are of comparable light output if of comparable physical type. V. good for brightest cluster members.

Expansion of Universe.

Galaxy spectra. *Slide*: Tiny. Superimposed stellar spectra, absorption lines

Slide: Proportion of red shifts, H&K Ca lines.

Slide: Velocity : distance relation.

How to explain?

Not an explanation, but a rationalisation. All matter attracts gravitationally. ~~[illegible]~~ If gravity is universal, no static distribution of masses can remain separated → collapse to a central glob.

We are not living in a glob.

Possibilities for non-glob Universes:

1. Contraction (we are on our way to becoming a glob)
2. Expansion (we are being blown ~~up~~ away from a past glob)
3. Revolution (everything is revolving around a mass centre)
4. Gravity is __not__ the only large-scale force, e.g. Einstein's cosmic repulsive force.

(1) and (3) ruled out by experience.
(4) is fairly arbitrary, given the modern data.
(2) → Something in the past inflicted a ~~[illegible]~~ motion of expansion.

(2) has following consequences.

Slide There was a singular time in the past. $t = 0$ Moment of Creation. Big Bang.

It should be possible to __date__ it by observing kinematics of the expansion.

Neo-Newtonian cosmology. (Slide)

Sphere of radius r centred on the ex-glob.

$v = H_0 r$ $M = \frac{4}{3}\pi \rho_0 r^3$

$\therefore T_m = \frac{1}{2} m v^2 = \frac{1}{2} m H_0^2 r^2$

$V_m = -\frac{GMm}{r} = -\frac{G \cdot \frac{4}{3}\pi r^3 \bar{\rho}_0 \cdot m}{r} = -\frac{4\pi G \bar{\rho}_0 m r^2}{3}$

Expansion will be halted / just halted / for ever if $\bar{\rho}_0 \gtreqless \frac{3H_0^2}{8\pi G}$

Slide Scale factor for universal distances as f(t).

In principle. – Measure H_0, ρ_0, we know which situation we have. Can then "date" the bang. This → "age of the world."

Cosmologists work with a dimensionless deceleration parameter

$$q_0 = -\frac{\ddot{R}_0 R_0}{\dot{R}_0^2} \qquad q_0 \gtreqless \frac{1}{2} \rightarrow \text{the different models.}$$

For $q_0 = \frac{1}{2}$, "Age of Universe" $= \frac{2}{3}\left(\frac{1}{H_0}\right)$ · just-expanding model

$q_0 = 0$ $= \frac{1}{H_0}$ —— negligible deceleration.

So $\frac{1}{H_0}$ → an upper limit to the "Age of the Universe".

1pc = 3×10^{13} km
1Mpc = 3×10^{19} km

When these ideas were first put forward, H_0 = 558 km/sec/Mpc or 558×10^{-12} yrs^{-1}

$1/H_0 \sim 2\times10^9$ years.

So the "age of the Universe" was < 2 billion years. This was < age of Earth.

The steady-state model was introduced to get around this problem.

Slide.

No cosmic clock. Average galaxy density constant.
Hubble's constant constant.
Continuous creation of material to "fill up the gaps",

matter created with the correct expansion velocity. A still-active Creator, no definable "age of the Universe". $\dot{M}/M = \frac{3Hne^{3Ht}}{ne^{3Ht}} \sim 3H \sim 5\times10^{-18}\,sec^{-1}$!

Slide. But the stars were further away than they looked.

Hubble had compared Cepheids in the spiral arms of ~~distant~~ nearby galaxies with those in the ~~nuclear bulge~~ spheroidal halo of our own. (∵ of the dust problem). Differences in chemical composition between these first- and second-generation stars screwed up his calibration of the nearby galaxies and clusters. Also was confusing brightest stars in distant clusters with clumps of stars.

Modern H_0 = 50 km/sec/Mpc → $\frac{1}{H_0}$ = 20 billion years.
(Puerto Rico, Dec 1971). No sweat.

Tests.

1) BB radiation. In an expansion $\rho_{matter} \propto \frac{1}{scale^3}$

but $\rho_{radiation} \propto \frac{1}{scale^4}$ ← because radiation exerts a finite pressure & does work in an expanding world.

So a Universe with any radiation today must have been radiation-dominated in its compact past. → Big Bang was a "radiation Universe" or fireball.

Radiation was in equilibrium with dense matter → BB radiation.

Expansion of Universe redshifts this radiation, cools it, maintaining BB law. If there was a BBang, should be an isotropic radiative BB background today.

1965 Penzias & Wilson at Bell Tel Labs in Holmdel, N.J. were calibrating a horn antenna originally set up for the Echo satellite program, at 4080 MHz. To test performance they pointed at sky and saw if they got ~~[illegible]~~ background brightness extrapolated from low frequencies, where there is a known radio background from interstellar cosmic rays. They found too much rad", coming in isotropically, and thought they had a noisy antenna (signal was ~ 3°K worth).

Meanwhile Big-Bang cosmology group at Princeton had made ball-park calculations to show relict radiation should be BB with peak in the short cm range, where P & W. were operating. When Dicke went to New Jersey to compare techniques...

<u>BB radiation</u> Slide. Rayleigh-Jeans law only.
~2.7°K.

Crucial to the Big Bang interpretation that it be Black Body, isotropic.

Isotropy is good to better than 0.1%.

Black-body not so well known ∵ the peak is in the region for worse infrared work, due to water vapor in Earth's atmosphere. Interstellar Cyanogen has a rotational excitation out of the ground state at 2.6mm. Electronic transitions in the visible show split CN absorption lines giving a 2.6mm intensity of ~ 3°K. But still need the short-λ side of the curve. If <u>any</u> CN showed ground-state line <u>only</u>, the rad" could not be Universal.

Non-linearity of Hubble Law.

This would give a measure of q_0. Need a "standard candle" which can be recognised at great distances. The giant ellipticals are used. Plot z versus apparent brightness and look for deviation from the linear law. This test works best for st-st., gives $q_0 \sim 1$ (oscillating model), but uncertainty is $\sim \pm 1$.

Difficulties due to getting photometry of faint diffuse objects against bright night sky background. Also some uncertainty about corrections to the light output of the "standard candles" due to long look-back time (~ 6 million years). Recent work shows that colours of the distant galaxies are same as those of nearby (after allowing for the redshift). ∴ ~~[illegible]~~ Stellar populations prob much same and the evolutionary corrections are small. (Galaxies should redden with age).

Could improve on this by finding more bright ellipticals at greater distances. Surveys with giant optical telescopes impractical due to their small fields of view, ∴ need help. Help comes from radio astronomy ∵ these brighter cluster members are preferentially radio sources.

Slide. Cyg A source. Optical identifications.

Slide. Trouble. M87 jet, M82 > pathological non-"standard candles" which could creep in.

Abundance of the elements.

Big Bang has high-density matter at high temperature.

Gamow model. Assume all matter could be combined into neutrons.

While $T > 10^{10}$ K, the radiation can create electron-positron pairs. These bring ~~on~~ a thermal equilibrium balance to

$$\gamma + \gamma \rightleftharpoons e^+ + e^-$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$
$$p + e^- \rightleftharpoons n + \nu$$

$$\frac{n}{p} = \exp\left[-\frac{\Delta mc^2}{kT}\right]$$

After the Universe cooled below 10^{10} °K, the neutrons proceed to form helium nuclei by ordinary neutron capture. ∵ of the equilibrium n/p situation, the model predicts a He/H ratio of ~ 10% by number for a wide range of starting conditions. ~ 30% by mass.

<u>Slide</u> He/H fraction as fn of $\bar{\rho}$ at $T = 10^{10}$ °K.

[Now $\rho_r \sim T^4 \sim 1/R^4$
$\rho_m \sim 1/R^3$
∴ $T^3 \rho_m \sim$ constant.
after the radiation has decoupled]

If we take <u>present</u> $T \sim 3$°K
$\bar{\rho}_{galaxies} \ll \bar{\rho}$, we find we are <u>just</u> on the plateau at the low-density side. If $\bar{\rho}$ is > $\bar{\rho}_{galaxies}$, we are on the plateau. If $\bar{\rho}$ is estimated from observed q_0, we are on the plateau. The plateau abundance is close to the average He/H abundance observed in stars and nebulae in our galaxy. This abundance is <u>much</u> higher than would be achieved through stellar synthesis which is only ~ 1% by <u>number</u>. This is a coincidence?

A final coincidence.

Estimate "age of Universe" from H_0 and q_0, at ~ 12 billion years.

This is comparable with estimates from astrophysics of the ages of the oldest stellar populations in galaxies (the red-giant rich "halo" populations". These ~~[illegible]~~ metal-poor stellar populations almost certainly should represent primeval material in stellar form. The age estimates, based on main-sequence turn-off, fit the reciprocal Hubble time nicely.

Galaxy formation.

Two critical epochs in history of Universe.

First is the time when ρ_{rad} first gets down to ρ_{matter}, $T \sim 100{,}000\,K$
$t \approx 1000$ years.

Second is the time when T gets down to ~ 4000 K, $t \sim 10^5$ years.
After the second time, electrons can be captured into atoms and free-electron scattering of the radiation background very effectively decouples matter and radiation. Radiation pressure will then no longer prevent gravitational condensations. Studies of the stability of condensations in the early Universe show that one of the preferred sizes at this critical time is $\sim 10^{12} M_\odot$, near the UL galaxy masses.

Prognosis for future.

Crucial data.: Are the QSS cosmological?

Is the BB radiation really BB?

Can we push really faint galaxies on the z-m relation to determine q_0.

Can we improve our knowledge of $\bar{\rho}$?