

**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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    - Hubble’s law ~1930
      - from antiquity Universe had been assumed to be static
      - relativity naturally expects universe to expand or contract, but very few people took this literally
      - Alexander Friedmann
      - Georges Lemaitre
      - not Einstein!
    - expansion eventually discovered by observation
The expanding universe

- At $z << 1$ all cosmological models expect a linear behaviour, $z \propto d$
  - first evidence: Edwin Hubble 1929
    - "the possibility that the velocity-distance relation may represent the de Sitter effect"
    - slope of graph: $465 \pm 50$ km/s/Mpc or $513 \pm 60$ km/s/Mpc (individual vs grouped)
    - assumption of linearity
      - no centre to expansion
      - established by 1931 (Hubble & Humason)

Hubble's law

- Timeline
  - 1907: Bertram Boltwood dates rocks to 0.4 – 2.2 Gyr (U-Pb)
  - 1915: Vesto Slipher demonstrates that most galaxies are redshifted
  - 1925: Hubble identifies Cepheids in M31 and M33
  - 1927: Arthur Holmes – "age of Earth’s crust is 1.6 – 3.0 Gyr"
  - 1929: Hubble's constant value of 500 km/s/Mpc implies age of Universe ~2.0 Gyr
  - potential problem here…

- Hubble's law systematics
  - distances mostly depend on $m - M = 5 \log(d/10)$ (luminosity distance)
  - getting $M$ wrong changes $d$ by a factor of $10^{(M - M_{\text{est}})/5}$
    which does not affect linearity (just changes slope)
  - typical systematic error: very difficult to spot
    - Jan Oort expressed doubts very quickly (1931)
    - no-one else till 1951!
**Hubble’s distances**

- Hubble used
  - Cepheid variables as calibrated by Shapley (1930)
  - brightest stars in galaxies as calibrated by Cepheids
  - total luminosities of galaxies calibrated by Cepheids and brightest stars

Wrong by factor of 2!

Wrong by factor of ~4!

Wrong because calibration wrong

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**Cepheids**

- Shapley (1930):
  - calibration of extragalactic Cepheids based on assumption of consistency with RR Lyrae variables in globular clusters

- Baade (1952):
  - Cepheids in Magellanic Clouds (δ Cephei stars or classical Cepheids) are different from “Cepheids” in globular clusters (W Vir stars or Type II Cepheids)

Typical classical Cepheid and W Vir light curves from the HIPPARCOS database
Cepheids

- Period-luminosity relation
  - RR Lyrae stars
    - period < 1 day
    - \( M \approx 0.7 \) (on horizontal branch)
    - little evidence of dependence on period (does depend on metallicity)
  - W Vir stars
    - period > 10 days
    - post-horizontal-branch low mass stars
  - classical Cepheids
    - period > 1 day
    - post-main-sequence stars of a few solar masses

- Distance error
  - from +0.7 to −0.7: ~ factor 2

Brightest stars

- Idea: brightest stars in all galaxies are about the same absolute magnitude
  - not unreasonable: tip of red giant branch is still used as distance indicator
  - might worry about age and metallicity effects
  - but first be sure you are looking at a star!
    - Hubble wasn’t: he was seeing H II regions (ionised gas around young massive stars)
    - these are much brighter than individual stars
    - difference ~2 mag
**Stars and H II regions**

M100 spiral arm


**History of H_o**

Compilation by John Huchra

Baade identifies Pop. I and II Cepheids

“Brightest stars” identified as H II regions

Jan Oort
Hubble Wars

- Distance indicators
  - Stars, clusters, etc.
    - classical Cepheids
    - novae
    - globular clusters
    - planetary nebulae
    - supernovae Ia and II
  - Galaxies
    - Tully-Fisher
    - Fundamental plane
  - Bigger things
    - Sunyaev-Zeldovich effect
    - gravitational lensing

- Sources of uncertainty
  - calibration
    - zero point
    - dependence on age, metallicity, galaxy type, etc.
    - reddening corrections
  - bias
    - Malmquist bias
      - at large distances, you tend to detect brighter than average objects
    - personal biases too!
      - Allan Sandage: low
      - Gerard de Vaucouleurs: high

reasonable convergence only in last decade – see later
**Hubble’s law & expansion**

- Does Hubble’s law mean universe is expanding (i.e. \( a(t) \) in RW metric not constant)?
  - Alternative hypotheses
    - real explosion at some past time
      - over time \( t \) galaxies travel distance \( d = vt \), so build up Hubble law
      - don’t expect to be at centre of expansion, so don’t expect isotropy
    - “tired light”: light loses energy \( \propto \) distance travelled
      - tested by looking at surface brightness:
        - tired light: object at redshift \( z \) has surface brightness \( \propto (1+z)^{-1} \)
        - expansion: object at redshift \( z \) has surface brightness \( \propto (1+z)^{-4} \)
      - 1 from energy loss, 1 from reduction in reception rate of photons, 2 from relativistic aberration

**Tests of tired light**

- **Surface brightness**
  - results consistent with expansion
    - correcting for galaxy evolution
- **Supernova light curves**
  - effect of time dilation
- **Cosmic microwave background**
  - not expected to have blackbody spectrum in tired light models

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State of Play ~1990

- Hubble’s law $v = H_0d$ well established
  - actual value of $H_0$ uncertain by a factor of 2
- Interpretation of Hubble’s law well established
  - surface brightness tests indicate expansion, not “tired light”
- Return of worries about age of universe
  - values of $H_0$ above ~80 km/s/Mpc looking suspiciously inconsistent with globular cluster ages
    - in flat universe without $\Lambda$, 80 km/s/Mpc gives age 8 Gyr
    - globular cluster ages from stellar evolution ~12 Gyr