Measuring the Expansion Rate of the Universe

Is ‘Hubble’s Constant’ constant?

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Edwin Hubble (1889-1953)

Four major accomplishments in extragalactic astronomy:

- The establishment of the Hubble classification scheme of galaxies
- The convincing proof that galaxies are island “universes”
- The distribution of galaxies in space
- The discovery that the Universe is expanding
Doppler effect

Light from distant astronomical objects is redshifted:

$z=0$: not moving
$z=2$: $v=0.8c$
$z=\infty$: $v=c$

$z := \frac{\delta \lambda}{\lambda}$; \quad 1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}}$
The redshift (velocity) - distance relation

Hubble 1929

(1pc ≈ 3 \cdot 10^{16} m ≈ 3.26Lj)
A “modern” Hubble diagram
Hubble’s “law”

\[ v = H_0 d \]

\( v = \) recession velocity in km/sec
\( d = \) distance in Mpc
\( H_0 = \) expansion rate today (Hubble Parameter)

In words:
The more distant a galaxy, the faster its recession velocity.
Hubble’s “law”

Expanding Universe: (empty?) space is created!
The basis: Einstein’s General Relativity
The basis of Cosmology:

The Universe is homogenous and isotropic \( \Rightarrow \)

space of constant curvature \( k \)

\[ \Omega_0 = \frac{\rho_0}{\rho_c} = \frac{8\pi G \rho_0}{3H_0^2} \]

- \( \Omega_0 > 1 \) \( k > 0 \)
- \( \Omega_0 = 1 \) \( k = 0 \)
- \( \Omega_0 < 1 \) \( k < 0 \)
Mean distance between galaxies today is fainter. The fate of the Universe depends on the value of $\Omega_0$, which represents the mean density of the Universe:

- $\Omega_0 = 0$: Closed universe
- $\Omega_0 < 1$: Open universe
- $\Omega_0 = 1$: Critical universe
- $\Omega_0 > 1$: Closed universe

Redshift is observed as the universe expands, making distant objects appear fainter. The scale is marked in billion years:

- 14 billion years
- 9 billion years
- 7 billion years
- Today
The basis: Einstein’s General Relativity

\[ -\Lambda g_{\mu\nu} \]
Hubble’s `law’

\[ v = H_0 d \]

\( v \) = recession velocity in km/sec
\( d \) = distance in Mpc
\( H_0 \) = expansion rate today (Hubble Parameter)

In words:
The more distant a galaxy, the faster its recession velocity.

**Problem:** How to measure \( d \)?

*(Hubble got it wrong by more than a factor of 10!)*
How do we measure distances in “daily life”?

- Parallaxes
- Travel time
- Via size of objects: comparison with standard yard sticks
- Via brightness of objects: comparison with standard candles
Parallaxes

- Measure the position of an object in the sky with respect to its background.
- Nearby objects show a larger apparent “motion” than objects far away do.
- The parallax angle $\theta$, the distance of the object $d$ and the diameter of the Earth’s orbit $D$ are connected by simple geometrical relations. For small angles, it is $D = d \times \theta$. 

![Diagram showing parallax effect and parallax angle](image)
Travel time

- If you know the speed $v$ you are traveling with and the travel time $\Delta t$, the distance $d$ can be obtained by simple multiplication:
  $$d = v \Delta t$$

- Astronomy: Use light travel times, i.e. $v = 300,000 \text{ km/sec}$

- Example: gravitational lensing, time delays
Comparison with a standard ruler

• If the physical size $l$ of an object is known (⇒ “standard ruler”), its distance $d$ can be determined by measuring the angle $q$ under which the object appears.

• For small angles, it is $l = d \times q$

• **Note:** The “standard ruler” has to be calibrated (in most cases)!

• Example: Cosmic microwave background
Comparison with a standard candle

- The absolute luminosity of an object, its distance and its apparent luminosity are connected by:
  \[ L_{\text{apparent}} = \frac{L_{\text{absolute}}}{d^2} \]

- If the absolute luminosity of an object is known (⇒ “standard candle”), its distance can be determined by measuring its apparent luminosity.

- **Note:** The “standard candle” has to be calibrated (in most cases)!
Comparison with a standard candles

• Example 1: δ Cephei stars
Comparison with a standard candles

- Example 1: δ Cephei stars

Storm et al. (2011)
Comparison with a standard candles

- Example 2: Type Ia supernovae (SN Ia)
Comparison with a standard candles

• Example 2: Type Ia supernovae (SN Ia)
  - highly evolved, H-deficient low mass stars (white dwarfs)
  - explosive C and O burning
  - binary systems required
  - complete disruption (in most cases)
  - Light curve dominated by energy release from radioactive decay
    \(^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}\)
Comparison with a standard candles

- **Example 2: Type Ia supernovae (SN Ia)**

(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

**After calibration:** SN Ia good “standard candles”!
The most recent supernova Hubble diagram

(Scolnic et al., 2018)

$\Omega_m = 0.307 \pm 0.012$

$w = -1.026 \pm 0.041$

($H_0 = 68.0 \pm 0.86$)
The Distance Ladder

ladder to reach objects in Hubble flow ($v_{\text{peculiar}} \ll v_{\text{Hubble}} = H_0 d$)

1 (Kpc) 2 (Mpc) 3 (Gpc)

1: Geometry $\rightarrow$ Cepheids  2: Cepheids $\rightarrow$ SN Ia  3: SN Ia $\rightarrow z, H_0$

[slide material courtesy of Adam Riess]
Distance Ladder measurements

• Hubble Space Telescope Key Project [Freedman et al. 2001]
  • $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (10% uncertainty)
  • resolving multi-decade “factor-of-two” controversy

• Carnegie Hubble Program [Freedman et al. 2012]
  • $H_0 = 74.3 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (2.8% uncertainty)

• Carnegie-Chicago Hubble Program [Beaton et al. 2016]
  • aim 3% precision in $H_0$ via independent route with RR Lyrae, the tip of red giant branch, SN Ia

• Supernovae, $H_0$ for the dark energy Equation of State (“SHOES”) project [Riess et al. 2016]
$H_0$ from SH0ES

19 Calibrations

15 Parallaxes + 3 anchors

Geometry $\rightarrow$ Cepheids

Geometry: $5\log D$ [Mpc] + 25

Cepheid: $m-M$ (mag)

SN Ia: $m-M$ (mag)

$\mu(z)$, $H_0=73.24 +/- 1.74$, Km s$^{-1}$ Mpc$^{-1}$

2.4% total uncertainty

[Riess et al. 2016]

[slide material courtesy of Adam Riess]
The Cosmic Microwave Background

- **Perfect blackbody radiation is the signature of the early equilibrium**
- **Observed by balloon and satellite experiments**

*Fig. 4.—Uniform spectrum and fit to Planck blackbody ($T$). Uncertainties are a small fraction of the line thickness.*
CMB: Fluctuations on the mK and μK level

$T = 2.728 \text{ K}$

$\Delta T = 3.353 \text{ mK}$

$\Delta T = 18 \text{ μK}$

COBE maps.
The CMB μK-scale fluctuations

Planck Surveyor
Where do CMB fluctuations come from?

- **Wrinkles**: some regions have a slightly higher gravity, some a slightly lower ("potential wells")
- **Matter falls into potential wells**

"Wrinkles" or Hills & Valleys

Accumulation in Valleys
Can we “see” the “sound” of the universe?

• Compressed gas heats up

⇒ temperature fluctuations
Use CMB as “Standard Ruler”

- Work in Fourier space
- Power spectrum of temperature fluctuations

Note: Interpretation requires a cosmological model (e.g., ΛCDM)!
(1) Ratio of peak heights $\rightarrow \Omega_m h^2, \Omega_b h^2$

$h = H_0 / 100 \text{ km/s/Mpc}$

(2) Location of the first peak in flat $\Lambda$CDM $\rightarrow \Omega_m h^{3.2}$

- **Flat $\Lambda$CDM** assumption: $h = 0.678 \pm 0.009$ [Planck]
- Without flat $\Lambda$CDM assumption, $h$ highly degenerate with other cosmological parameters.
Hubble Constant: recent results

Global determination
- Planck15+$\Lambda$CDM
- WMAP9yr+SPT+ACT+BAO+$\Lambda$CDM

Local determination
- Here
- R11
- E14(R11)

Non-SN Ia Ave.
- IRTF
- Lensing
- SZ Clusters

Masers

$\Delta w_0 = -0.1$
$\Delta w_a = -1$
$\Delta N_{\text{eff}} = +1$
$\Delta \Omega_K = -0.01$

Riess et al. 2016
Hubble Constant: a key parameter!

Measure:
- age, size of the Universe
- expansion rate: $v = H_0 d$

Enters into the determination of most other cosmological parameters as a scaling factor ($h$, $h^2$; e.g., energy and mass density, baryon density, ...)

- Tension (on the 2-3 $\sigma$ level) between most advanced methods!
- Real? (Local) inhomogeneity? New physics?

→ Need more precise determination of $H_0$!
Hubble Constant: a key parameter!

Need Independent methods to overcome systematics, especially the unknown unknowns

If possible: **Absolute distances**!

**Two examples:**

- **Type IIP supernovae** and the “expanding photosphere” method
- “**Gravitational lensing**” (of type IIP and type Ia supernovae)
Type IIP ("core collapse") supernovae

- High mass stars (>8M☉)
- Extended envelopes (still burning)
- Single stars
- Collapse to neutron star or black hole

Crab nebula with pulsar (constellation Orion)
Remnant of a supernova observed in 1054
A few observational facts

> Very bright events:
  \[ L \sim 10^{10} \, L_{\text{sun}} \]

> Fast expanding ejecta:
  \[ v \sim 10^4 \, \text{km/s} \]

> Energies:
  - Electromagnetic
    \[ \sim 10^{42} \, \text{J} \]
  - Kinetic
    \[ \sim 10^{44} \, \text{J} \]
  - Neutrinos (SN1987A):
    \[ \sim 3 \cdot 10^{46} \, \text{J} \]

> Progenitor star destroyed (SN 1987A, SN 1993J, ...)

> Compact remnant (as far as we know)
Expanding photosphere method

- Measure the increase in size of a (type IIP) supernova

\[ R_{ph} = x_0 + v_{ph}(t)(t - t_0) \]

- Observed flux depends on the surface area
  - Assume blackbody radiation

\[ f_\lambda = \left( \frac{R_{ph}}{D} \right)^2 \pi B_\lambda(T) = \theta^2 \pi B_\lambda(T) \]

(D: distance; \(B_\lambda\): Planck function)
Expanding photosphere method

- **Solve for** \( t_0 \) and \( D \)

\[
t = D \left( \frac{\theta}{v_{ph}} \right) + t_0
\]

- **Together with redshift:** \( H_0 \)
Expanding photosphere method

Main problem: supernova radiation is not a black body!

Origin of BB photons: thermalisation radius $R_{th}$

Photosphere: surface of last scattering ($R_{ph} > R_{th}$)
Expanding photosphere method

Main problem: supernova radiation is not black body!

Radiation is “diluted” in the blue and UV bands!

Corrected for by means of a “dilution factor” $\varsigma$.

\[
f_\lambda = \theta^2 \varsigma^2 \pi B_\lambda(T), \quad \varsigma = \frac{R_{\text{th}}}{R_{\text{ph}}}
\]

Dessart & Hillier 2005
Expanding photosphere method

From fits to models:

Dessart & Hillier (2005)

Eastman, Schmidt & Kirshner (1996)
Expanding photosphere method

Vogl et al. (2018)
Expanding photosphere method

An early EPM Hubble diagram
(16 SNe, dilution as in Eastman et al. 1996)

\[ H_0 = 73 \pm 6 \text{ (stat)} \pm 7 \text{ (syst)} \text{ [km/s/Mpc]} \]
Expanding photosphere method

**Recent improvements:**

- **“Tailored EPM”**: Spectral sequences used for individually determined dilution factors
- **“SEAM”**: Spectral-fitting Expanding Atmosphere Method, velocity and flux taken from spectral fitting
- Supernova SN 1999em as a benchmark: Cepheid distance $11.7 \pm 1.0$ Mpc (Leonard et al. 2003)
- Tailored EPM: $11.5 \pm 1.0$ Mpc (Dessart & Hillier 2006)
- SEAM: $12.4 \pm 2.4$ Mpc (Baron et al. 2004)
Expanding photosphere method

The future

- **SEAM** for a selected sample of SN IIP
- 20 SN IIP with redshifts between 0.01 and 0.04
- Typically 5 to 8 spectra
- Early discovery (→ $t_0$)
- Add several SN IIP at intermediate redshifts (up to $z \approx 0.3$)
Expanding photosphere method

Data quality
Expanding photosphere method

The most recent EPM Hubble diagram (Gall et al. 2018):

\[ \mu = 5 \log d - 5, \text{ d in pc} \]
Gravitationally lensed supernova
(courtesy Sherry Suyu, MPA)

Gravitational lensing:

Background star

Star's image

Sun

Earth
Strong optical lensing

Image credit: P. J. Marshall
Strong optical lensing

Mass “bends” light and acts likes a lens

Image Credit: P. J. Marshall
Gravitational lens

HST image: SLACS J 0737+3216

Image credit: P. J. Marshall

Strong gravitational lensing

B1608+656

Active galactic nucleus (AGN): accretion of material onto a supermassive black hole

Light emitted from AGN changes in time ("flickers")
Gravitational lens time delays

[Fassnacht et al. 1999, 2002]
Movie Credits:
S. H. Suyu, C. D. Fassnacht

NRAO/AUI/NSF
Gravitational lens time delays

**Time delay:**
\[ t = \frac{1}{c} D_\Delta t \phi_{lens} \]

**Time-delay distance:**
\[ D_\Delta t \propto \frac{1}{H_0} \]

Obtain from lens mass model

For cosmography, need:
1. time delays
2. lens mass model
3. mass along line of sight

**Advantages:**
- simple geometry and well-tested physics
- one-step physical measurement of a cosmological distance
$H_0$ from 3 strong lenses

$H \in [0,150] \text{ km/s/Mpc}$

$\Omega_m = 1 - \Omega_\Lambda \in [0,1]$  

$w = -1$

$H_0$ with 3.8% precision for flat $\Lambda$CDM!

[Bonvin, Courbin, Suyu et al. 2017]
$H_0$ with 3 lenses

3 Lenses
(H0LiCOW + COSMOGRAIL)

[Riess et al. 2016]
Supernova “Refsdal”

Discovered serendipitously in November 2014

[Kelly et al. 2015]
Supernova “Refsdal”

[Kelly et al. 2015]
Supernova “Refsdal”

Appearance of image SX: December 2015

[F125W + F160W (Dec 2015)]

[SX (New image)]

[S1, S2, S3, S4]

[F125W + F160W (Apr 2015)]

[SX (New image)]

[Kelly et al. 2016]
Supernova “Refsdal”

Predicted position (from lens models):

(courtesy Sherry Suyu)
Feasibility study of using SN Refsdal for $H_0$ measurement

- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)
First spatially-resolved lensed Type Ia

(Discovered in iPTF) [Goobar et al. 2017]

Problem
For this supernova: estimated time delay < 1 day! (Moore et al. 2017)

Future surveys: several 100 SNe!
Summary and outlook

- Hubble’s constant $H_0$ measures today’s expansion rate of the Universe and its age.
- It enters as a scaling factor into determinations of many other cosmological parameters.
- After a long-lasting debate, it is now determined to be around 70 km/s/Mpc, leading to an age of the Universe 13.8 Gyr.
- However, global (CMB) and local (Cepheids, SN Ia) determinations are inconsistent on the (2-3)$\sigma$ level.
- Real? Or systematic errors?
- If real: Universe inhomogeneous ("Hubble bubble") or "new physics" (sterile neutrinos, non-constant ‘dark energy’, ...)?
Summary and outlook

- The “Holy Grail”: Get $H_0$ with an error of less than 1%!
- New (and independent) methods show great promise
  - Better controlled systematics
  - Fewer steps in the distance ladder
- Examples discussed in this talk:
  - Type IIP supernovae (expanding photosphere method; several tens of events with multi-epoch high-resolution spectroscopy)
  - Gravitational lenses (quasars, supernovae; several hundred lenses)
- Necessary: should measure distances to objects in the Hubble flow
Summary and outlook

Systematics!

Hope is left in Pandora’s box

Thank you!