The Constantly Changing Hubble Constant

Lorne Whiteway
lorne.whiteway@star.ucl.ac.uk

Astrophysics Group
Department of Physics and Astronomy
University College London

Presentation to the Mid Kent Astronomical Society
12 November 2021

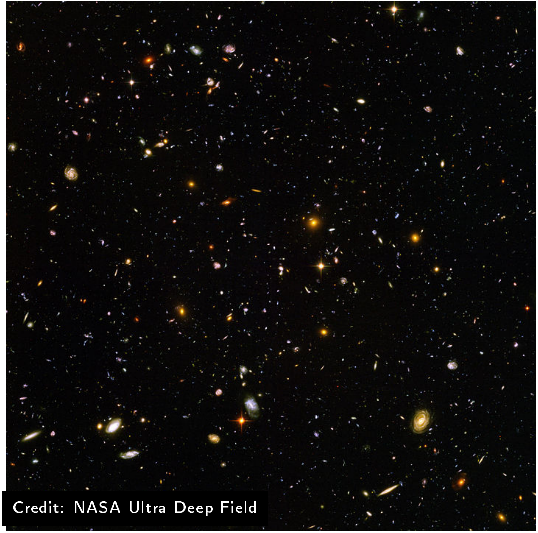
You are invited to go to www.menti.com and enter code 14 11 05 9.

The Universe is expanding!

- But what does this actually mean?
- How do we know it is expanding?
- Why is it expanding?
- How fast is it expanding?
- How do we know how fast it is expanding?
- Is the expansion rate changing?

How do we know?

- Everywhere we look, distant galaxies are receding; more distant galaxies are receding faster.
- So either we are at the centre of a cosmic conspiracy, or all the space between all the galaxies is expanding.


Credit: NASA Ultra Deep Field

Is the solar system expanding? Are *we* expanding?

Go to `www.menti.com` (code 14 11 05 9) and choose:

1. Yes, a lot
2. Yes, but only a tiny amount
3. No

Is the solar system expanding? Are *we* expanding?

Go to `www.menti.com` (code 14 11 05 9) and choose:

1. Yes, a lot
2. Yes, but only a tiny amount
3. No ✓

Is the solar system expanding? Are *we* expanding?

- Other forces - molecular forces between the molecules in your body, and gravitational forces between the Sun and the planets - are far more than strong enough to overcome the effect of cosmic expansion.

- Gravity is even strong enough to keep the Andromeda Galaxy from receding from us.

Credit: David Dayag

- It's only the furthest objects - where gravity becomes negligible - that recede.

What does *recession velocity* actually mean?

- We say ‘distant galaxies are moving away from us’. This is informal language.
- They aren’t really moving, they just appear to be - because the intervening space is expanding.
- Sometimes this distinction is important - for example, the recession velocity can exceed the speed of light.

Which ‘Ed’ first had the idea that the Universe is expanding?

Go to `www.menti.com` (code 14 11 05 9) and choose:

1. Edmond Halley
2. Edwin Hubble
3. Edgar Allan Poe

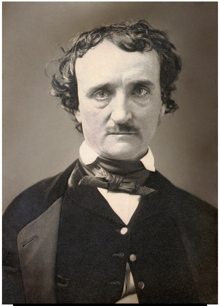
Which 'Ed' first had the idea that the Universe is expanding?

Go to `www.menti.com` (code 14 11 05 9) and choose:

1. Edmond Halley
2. Edwin Hubble
3. Edgar Allan Poe ✓

History

- In 1848 Edgar Allan Poe published *Eureka*, which included a description of expanding space.



Credit: Public domain

- Expansion is not obvious without large telescopes and so isn't usually part of pre-modern cosmologies. Full understanding only came in the 20th century.

So how fast is the expansion?

- For every additional distance of one megaparsec, there's an additional recession velocity of about 70 kilometers per second.
- So the expansion speed is about 70 kilometers per second per megaparsec.

- One megaparsec is about three million light years. It's the typical distance between galaxies.
- 70 kilometers per second is about 150,000 miles per hour.

So how fast is the expansion?

Start with a distance:

So how fast is the expansion?

Start with a distance:

13.5 million years later it will be 1% longer:

So how fast is the expansion?

Start with a distance:

13.5 million years later it will be 1% longer:

Continental drift is about six times faster...

H_0

- The current expansion rate is called the *Hubble constant* or *Hubble parameter* and is denoted 'H_0'.

- The 'H' commemorates Edwin Hubble (1889-1953), who was one of the first to measure it.

Credit: Johan Hagemeyer

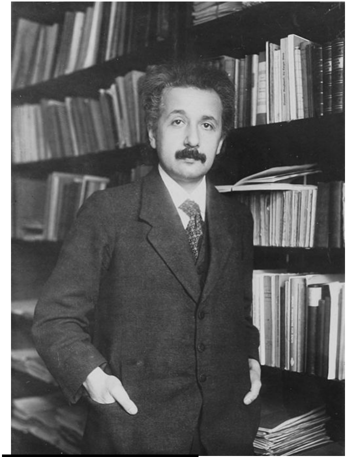
- The '0' refers to today. The expansion rate was different in the distant past.

Why does the Universe expand?

- Science is not so good with ‘why?’ questions...
- There’s an *initial condition*: the Universe started expanding at the Big Bang.
- The later behaviour of the expansion (does it slow down? speed up?) then depends, essentially via gravity, on *what’s in the Universe*.

Why does gravity play a role?

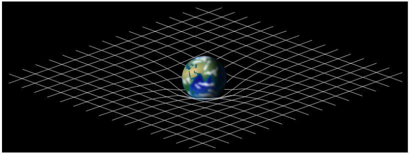
- *General relativity*, our modern theory of gravity, is due to Einstein (1916).



Credit: Paul Ehrenfest

Why does gravity play a role?

- Remember *mass* and *energy* are the same ($E = mc^2$).
- Mass/Energy *bends* spacetime, essentially changing distances and angles.



Credit: Mysid

Why does gravity play a role?

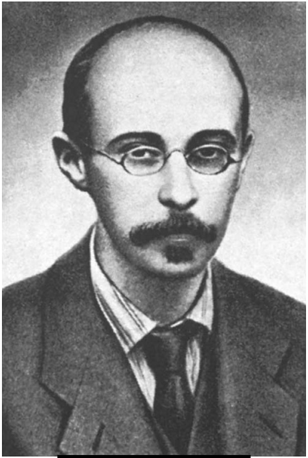
- This ‘changing of distances and angles’ works locally; the distorted spacetime governs how objects move, and this leads e.g. to the apple falling from the tree.

Why does gravity play a role?

- This ‘changing of distances and angles’ works locally; the distorted spacetime governs how objects move, and this leads e.g. to the apple falling from the tree.
- But it also works on the Universe as a whole - mass/energy can cause distances to change *everywhere* in the Universe - and in particular can lead to increasing distances everywhere. This is the expansion that we see.

Contents of Universe control expansion

- It was Alexander Friedmann (Алекса́ндр Алекса́ндрович Фри́дман) (1888-1925) who first realised this (1922).



Credit: Public domain

What if we go backwards in time?

- George Lamaître (1894-1966) realised that if the Universe was expanding then it must, at an earlier stage, have been very small; he thereby invented the idea of the 'Big Bang'.

Credit: Public domain

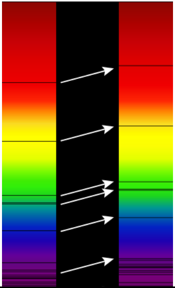
How do we measure the expansion rate?

- In theory it's easy: find a distant galaxy, measure its recession velocity and its distance, and take the ratio.
- Example: a galaxy is receding at 1600 kilometers per second and is 20 megaparsecs away;
  then H_0 is 80 kilometers per second per megaparsec.

Can use *redshift* to measure recession velocity

- Light from distant galaxies gets streeeetched by the expansion; this makes it turn redder.

- It's fairly easy to measure the amount of red-shifting, as spectral lines are a convenient reference point. The redshift then immediately gives the velocity.



Credit: Georg Wiora

V M Slipher

- The first redshifts for galaxies (known then as nebulae) were made in 1912 by Vesto Slipher (1875 - 1969) at the Lowell Observatory in Flagstaff Arizona.

Recession velocity for galaxy M77

From Slipher's 1917 'Lowell Observatory Bulletin 80':

These recent spectrograms have been measured for radial velocity. The results for the four spectrograms — two of 1913 and two of 1917 — are as follows:

Plate	1913,	November 6,	Velocity −1060 km.
Plate	1913,	November 22, 23,	Velocity −1150
Plate	1917,	November 6, 7, 8,	Velocity −1080
Plate	1917,	November 12 to 16, two prisms	Velocity −1130 *s*
			Velocity −1145 *c*
			Velocity −1135 *c*
		Mean Velocity	−1120 km.

Modern value (from NASA/IPAC Extragalactic database):

BASIC DATA for MESSIER 077 (Back to INDEX)

```
Helio. Radial Velocity     :      1137 +/-         3 km/s
Redshift                   :  0.003793 +/- 0.000010          2014MNRAS.440..696A
```

Can use Cepheids to measure distance

- Cosmic distances can be estimated using variable stars called *Cepheids*. We know how much light they produce (it's related to their period) - so they are *standard candles*. Their observed brightness then tells us their distance.

- The brightness/period relation was discovered by Henrietta Swan Leavitt (1868 - 1921) at Harvard.

Credit: Public Domain

How far away is that Cepheid?

A and B are two identical Cepheids; A is 100 parsecs distant; B is 4% of the brightness of A. How far is B?

Go to `www.menti.com` (code 14 11 05 9) and choose:

1. 500 parsecs
2. 2500 parsecs
3. 4 parsecs

How far away is that Cepheid?

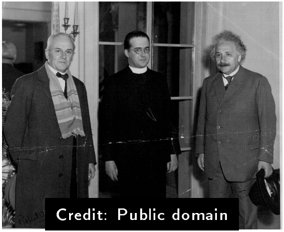
A and B are two identical Cepheids; A is 100 parsecs distant; B is 4% of the brightness of A. How far is B?

Go to `www.menti.com` (code 14 11 05 9) and choose:

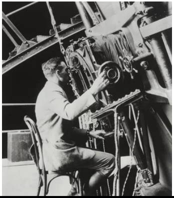
1. 500 parsecs ✓
2. 2500 parsecs
3. 4 parsecs

Recession velocity vs distance relationship

- It was Lamaitre who first suggested a linear relationship between recession velocity and distance.
- Hubble then provided supporting evidence - he used the 100 inch telescope at Mt Wilson to spot Cepheids in a range of galaxies.

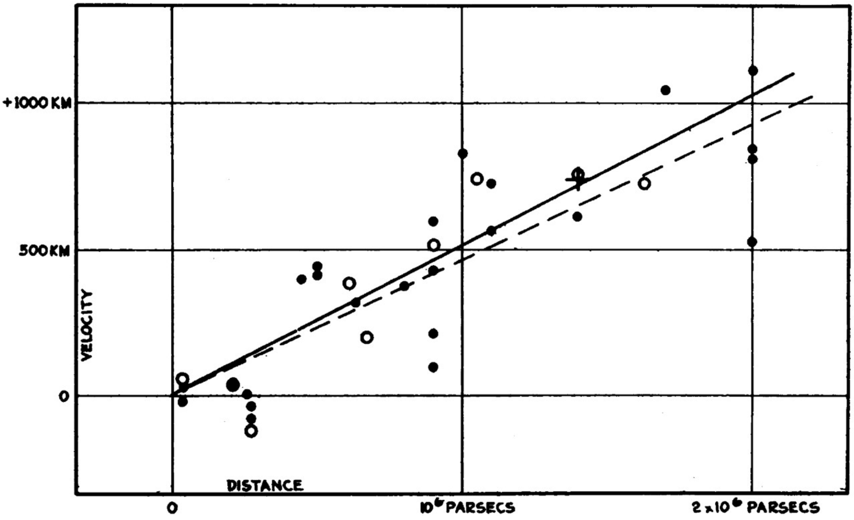


Credit: Public domain

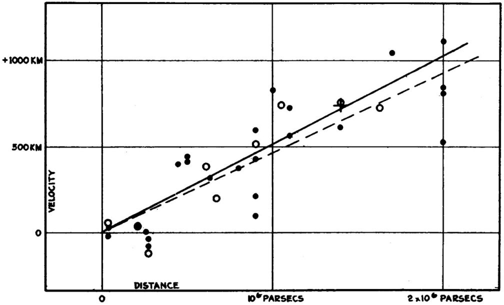


Credit: Edwin Hubble Papers

Hubble's plot - from 1929 PNAS paper



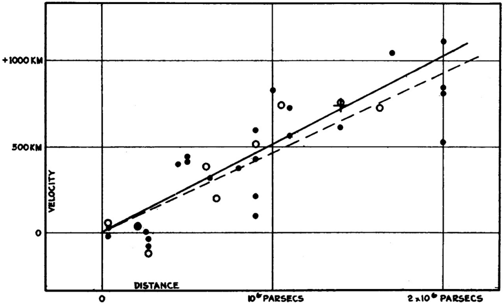
What value for H_0 does this plot give?



Go to `www.menti.com` (code 14 11 05 9) and choose:

1. 70 km per second per megaparsec
2. 100 km per second per megaparsec
3. 500 km per second per megaparsec

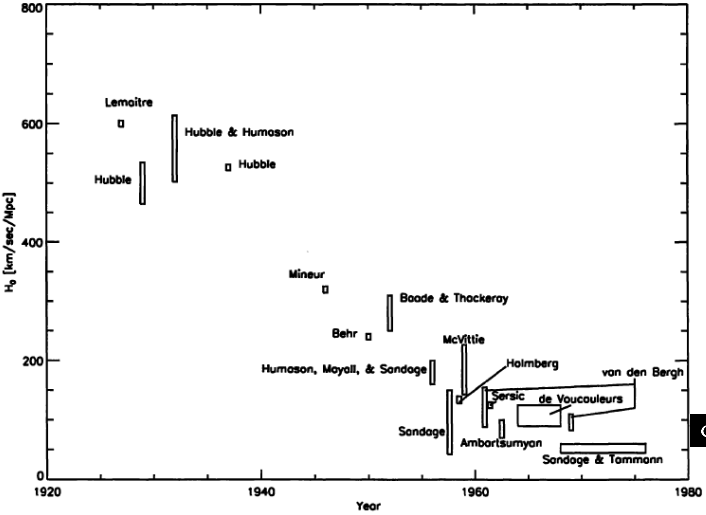
What value for H_0 does this plot give?



Go to `www.menti.com` (code 14 11 05 9) and choose:

1. 70 km per second per megaparsec
2. 100 km per second per megaparsec
3. 500 km per second per megaparsec ✓

Falling estimates of H_0 1920 - 1980



Credit: Trimble

Distances had been underestimated

Several revisions (distance up, H_0 down) followed:

1. Two types of Cepheids
2. Interstellar absorption of light
3. Scott effect (visible galaxies tend to be brighter than average)

Credit: MacTutor

4. Regions of hot gas were being misidentified as bright stars

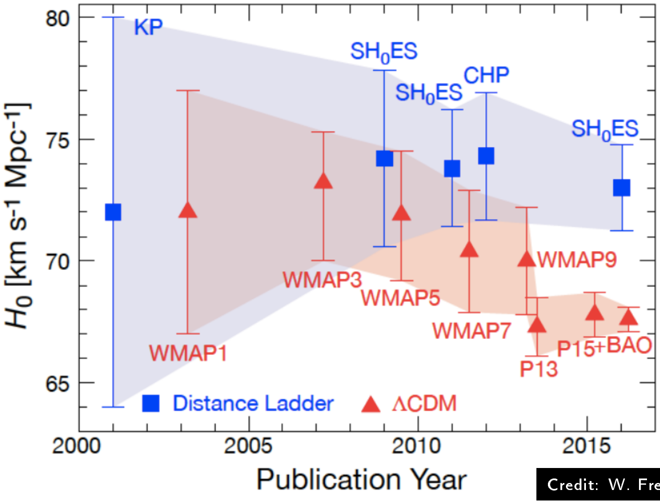
Hubble Space Telescope

- The Hubble Space Telescope was built (in part) to measure H_0.
- Lead investigator Wendy Freedman.

Credit: pollosaurio

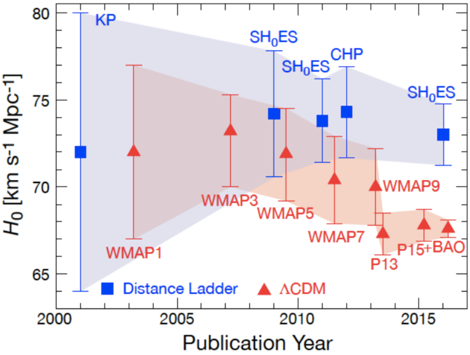
- Used supernovae as additional standard candles.
- $H_0 = 72 \pm 8$ kilometers per second per megaparsec.

More recent values - diverging opinion



Credit: W. Freedman

More recent values - diverging opinion



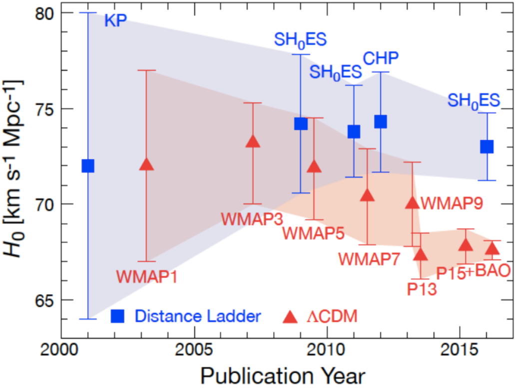
Credit: W. Freedman

- Blue results use standard candles: $H_0 = 74 \pm 1.4$ kilometers per second per megaparsec.
- Red results use data from the early Universe: 67.4 ± 0.6 kilometers per second per megaparsec.

H_0 from early Universe data

- For 300,000 years after the Big Bang, the Universe was opaque. Then it became transparent, and we can today observe (red-shifted) light from then (the *Cosmic Microwave Background)*.
- The distance that light could travel in those 300,000 years can be seen statistically in these observations. Trigonometry then gives us the distance the light has travelled.
- Redshift is easy - the spectrum has a prominent peak.
- Finally, correct for the evolution of H_0 from then to now.

Hubble tension

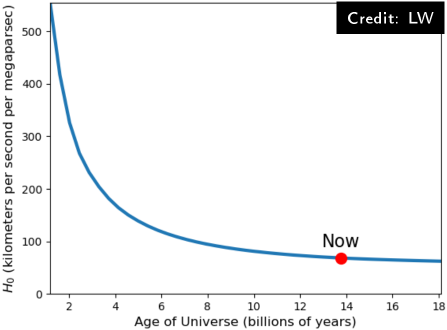


Credit: W. Freedman

Should we be worried by the discrepancy? It could indicate that our theory is wrong. But it might also just be a systematic error in one of the measurements.

Hubble constant - past and future

- H_0 isn't constant over cosmic timescales. The evolution is controlled by the contents of the Universe.



- Matter - mostly dark matter, but also hydrogen and helium - tends to push H_0 towards zero (no expansion).
- But the Universe also contains dark energy, and this opposes this trend. In the distant future the expansion will stabilise near 57 kilometers per second per megaparsec.

Where to find this document

- You can find the presentation at
  https://tinyurl.com/bycke8v6

Image credits

1. Hubble Deep Field: Source: NASA. From https://en.wikipedia.org/wiki/File:Hubble_ultra_deep_field_high_rez_edit1.jpg
2. M31: Source: David Dayag. Licensed under the Creative Commons Attribution-Share Alike 4.0 International license https://creativecommons.org/licenses/by-sa/4.0/deed.en. From https://upload.wikimedia.org/wikipedia/commons/thumb/8/8c/Andromeda_Galaxy_560mm_FL.jpg/1024px-Andromeda_Galaxy_560mm_FL.jpg.
3. Poe: Source: Public domain. From https://en.wikipedia.org/wiki/Edgar_Allan_Poe#/media/File:Edgar_Allan_Poe,_circa_1849,_restored,_squared_off.jpg
4. Hubble: Source: Public domain (by Johan Hagemeyer (1884-1962)). From https://commons.wikimedia.org/wiki/File:Studio_portrait_photograph_of_Edwin_Powell_Hubble.JPG
5. Einstein: Source: Public domain. From https://upload.wikimedia.org/wikipedia/commons/thumb/c/c3/08608_einstein_1916.jpg/512px-08608_einstein_1916.jpg
6. Curved spacetime: Source: Mysid. Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license https://creativecommons.org/licenses/by-sa/3.0/deed.en. From https://commons.wikimedia.org/wiki/File:Spacetime_lattice_analogy.svg
7. Friedmann: Source: Public domain. From https://upload.wikimedia.org/wikipedia/commons/6/62/Aleksandr_Fridman.png
8. Lemaître: Source: Public domain. From https://upload.wikimedia.org/wikipedia/commons/thumb/5/51/Georges_Lema%C3%AEtre_1930s.jpg/512px-Georges_Lema%C3%AEtre_1930s.jpg
9. Redshift: Source: Georg Wiora. Llicensed under the Creative Commons Attribution-Share Alike 2.5 Generic license https://creativecommons.org/licenses/by-sa/2.5/deed.en. From https://commons.wikimedia.org/wiki/File:Redshift.svg
10. Slipher: Source: Lowell Archive. Licensed under the Creative Commons Attribution-Share Alike 4.0 International license https://creativecommons.org/licenses/by-sa/4.0/deed.en. From https://upload.wikimedia.org/wikipedia/commons/a/a7/V.M._Slipher.gif, converted to png