The Most Distant Galaxies

Hubble's Law
Measurements of H_0
Quasars and Active Galaxies

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The Most Distant Galaxies

- Hubble's Law and the end of the distance ladder
- Current measurements of Hubble's constant H_0
- Active galaxies: the discovery of quasars
- Accretion power and the Eddington luminosity (or Eddington limit)

Reading: Kutner Ch. 18.5–18.6 and 19.4, Ryden Sec. 20.5 & 21.2

Artist's impression of ULAS J1120+0641, the first QSO observed at a redshift $z > 7$ (Mortlock et al. 2011).

Hubble's standard candles and rulers

After using Cepheid variables to estimate the distance to M31 and M33, Edwin Hubble continued to search for Cepheids in galaxies in which Slipher, Pease, and Humason were spectroscopically measuring radial velocities. By 1929, he had detected Cepheids in 10 galaxies with measured v_r (Hubble 1929).

Hubble used these galaxies to calibrate another **standard candle**: the tip of the red giant branch (TRGB). Because it is slightly brighter than the brightest Cepheids, this could, in principle, be used for galaxies too distant to detect Cepheids. (It also does not require measuring a pulsation period.)

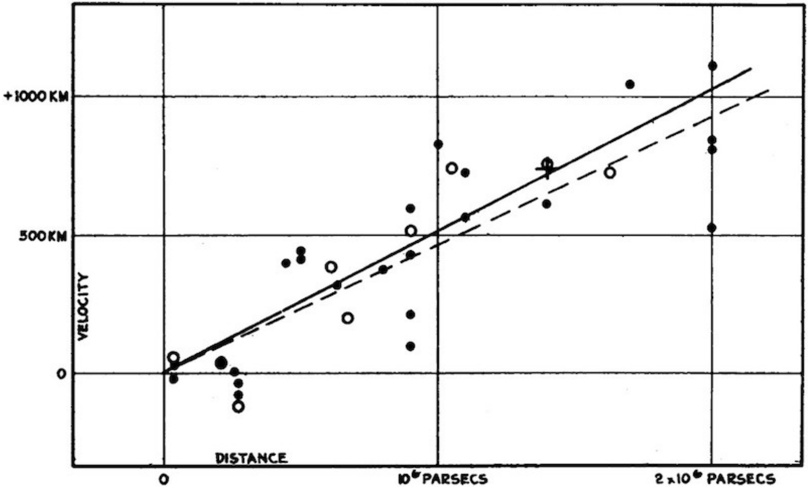
From observations of galaxies in clusters, Hubble noticed that galaxies of the same shape — i.e., Hubble type — were all about the same size. With Cepheid distances, he determined the size of nearby galaxies and could thereafter use those galaxy types as **standard rulers**.

Hubble's Law

After accumulating > 30 galaxies with measured v_r and distance d, Hubble plotted the two quantities and identified a linear relationship now known as **Hubble's Law** (Hubble 1929):

$$v_r = H_0 d$$

where
$H_0 = 500\ \mathrm{km/s/Mpc}$.



Hubble's Law

Hubble immediately realized that this linear relation would be the **ultimate distance indicator**, since the radial velocity of a galaxy can be determined completely independently of brightness or shape.

Though the linear form determined for the law was correct, the best-fit value estimated by Hubble for the constant of proportionality H_0 (now called **Hubble's constant**) was alarmingly large.

$H_0 = 500$ km s^{-1} Mpc^{-1} was a cause for concern even in 1929; it made the Milky Way look like the largest galaxy in the Universe by far. This (among other issues) was pointed out by Oort in 1931, who obtained $H_0 = 290$ km s^{-1} Mpc^{-1} in his own reanalysis of the data (Oort 1931).

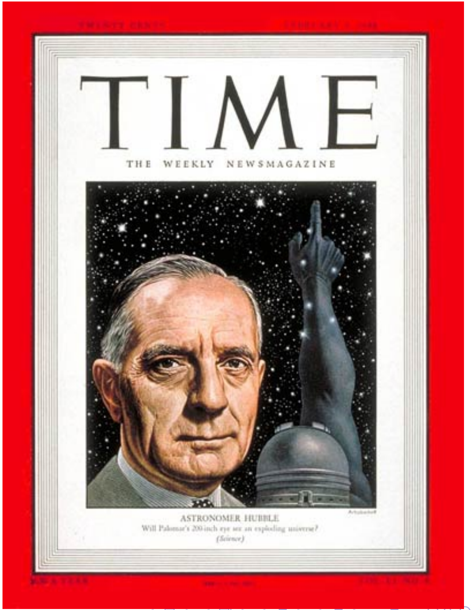
When interpreted as a measure of the expansion of the Universe, Hubble's H_0 implied the age of the Universe was 2 Gyr, less than the oldest radiometric ages of terrestrial rocks (~ 3 Gyr).

Hubble's Law

The overestimate of H_0 by Hubble (and Oort, and others) was due to the fact that the Cepheid calibration was **corrupted by extinction and multiple populations of pulsating stars**.

The mess was eventually cleared up by Baade (Baade 1944).

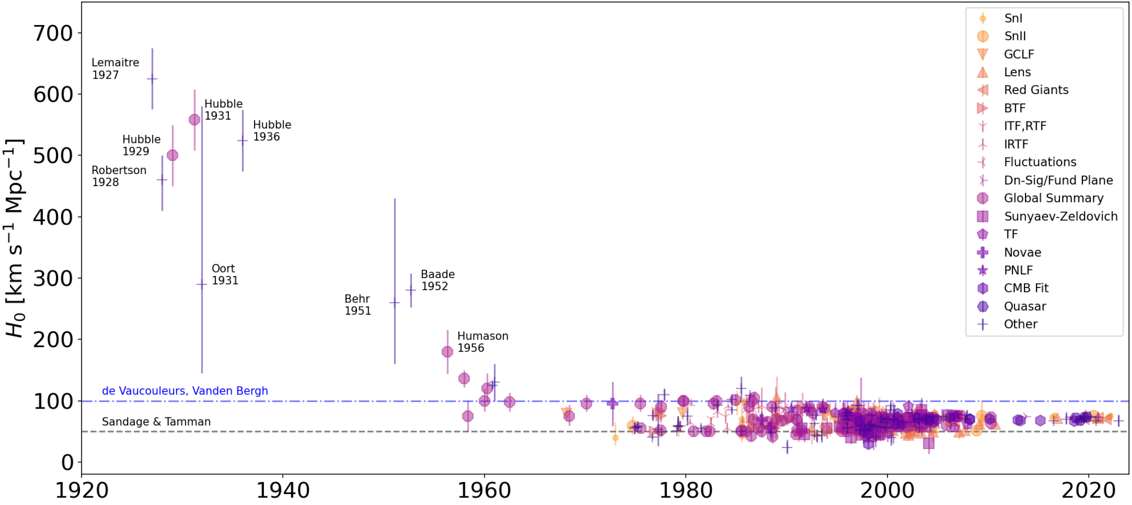
Hubble's Law also implies that the Universe expands. We will discuss this in detail later in the course; for today we simply use the law to measure distances to galaxies.



Edwin Hubble, 1948.

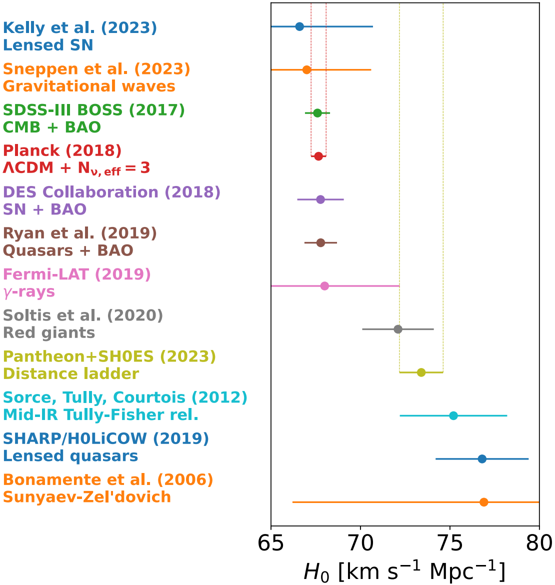
Measurements of H_0 over time

From measurements initially compiled by John Huchra, Harvard/CfA.



Recent measurements of H_0

Many groups are measuring H_0 using observations with very different systematic uncertainties.



Recent measurements of H_0

"Direct" and "indirect" methods for obtaining H_0:

- **SH0ES**: calibrated standard candles, going up the distance ladder from Cepheids to SNe Ia (Reid et al. 2022):

$$\boxed{H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}}$$

- **Planck**: indirect determination of H_0 via fits of cosmological models to the cosmic microwave background (CMB; Planck 2018):

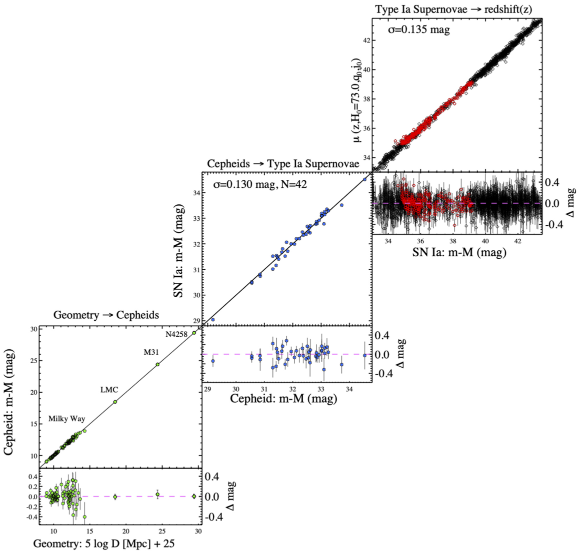
$$H_0 = 67.66 \pm 0.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Note there is a discrepancy at the "5σ level," i.e., a $3 \times 10^{-5}\%$ chance the disagreement is due to a statistical fluctuation, if we believe the error bars. Could be a systematic effect, or different physics affecting the CMB and standard candles. In this class, we will use the SH0ES value.

The complete distance ladder (SH0ES: 2022)

Measurement of H_0 using geometry and Cepheid-based distances, Cepheid and SN Ia-based distances, and SN Ia and redshift-based distances (Riess et al. 2022).

Calibrated distances on the x-axis are used to calibrate distance measures on the y-axis. A global fit is then performed using the full data set.



Redshift & radial velocity

By analogy with the form of the nonrelativistic Doppler shift expressed in terms of wavelength,

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_r}{c} \implies \lambda = \lambda_0 \left(1 + \frac{v_r}{c}\right)$$

astronomers define the **redshift** z:

$$\lambda = \lambda_0(1 + z) \implies z = \frac{\lambda - \lambda_0}{\lambda_0}$$

This form is used for all radial velocities, even if they are close to the speed of light. However, remember that

$$cz \approx v_r \quad \text{iff} \quad v_r \ll c$$

The largest redshift measured for an unlensed galaxy to date is $z = 13.20$! Note that the most distant object in Hubble's original sample was located at $z = 0.004$.

SN Ia apparent magnitude and distance

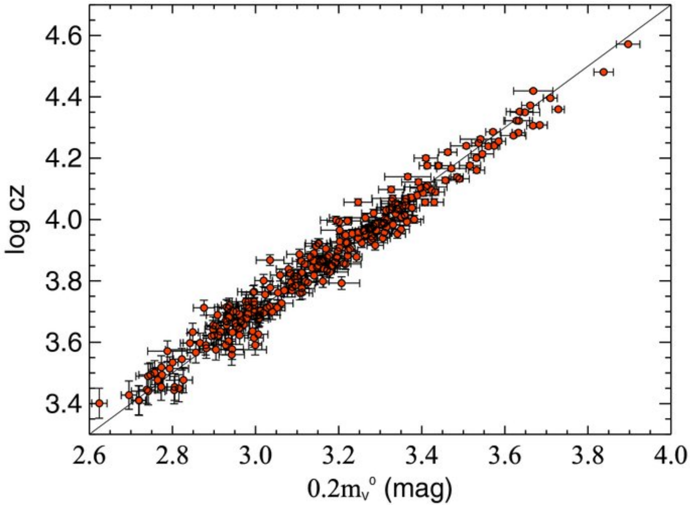
For convenience, *apparent magnitudes* of SNe Ia are often plotted, or referred to, instead of distance. The translation is

$$\begin{aligned} m_V^0 &= M_V^0 + 5\log\frac{d}{10\ \mathrm{pc}} \\ &= M_V^0 + 5\log\left(\frac{d}{10\ \mathrm{pc}}\cdot\frac{10^6\ \mathrm{pc}}{1\ \mathrm{Mpc}}\right) \\ &= M_V^0 + 5\log\frac{d}{\mathrm{Mpc}} + 25 \\ \log\frac{d}{\mathrm{Mpc}} &= 0.2m_V^0 - 0.2M_V^0 - 5 \end{aligned}$$

The absolute magnitude of a SN Ia is (Riess et al. 2011)

$$M_V^0 = -19.14$$

SN Ia Hubble Diagram



The intercept of the log-log plot (from Riess et al. 2011, Riess et al. 2009) gives H_0:

$$v_r = cz = H_0 d$$
$$\log cz = \log H_0 + \log d$$

m_V^0 can be converted to d using

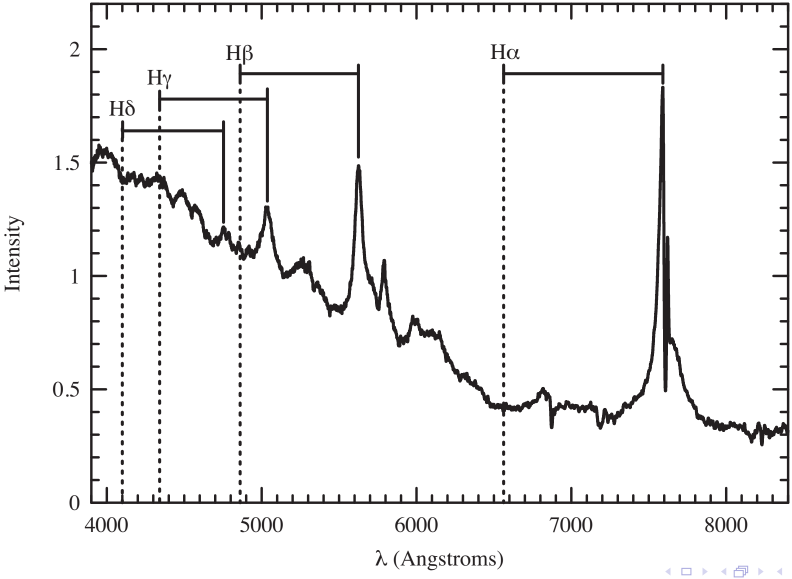
$$m_V^0 = 5 \log \left(\frac{d}{\mathrm{Mpc}} \right) + M_V^0 + 25$$

where $M_V^0 = -19.14$ (Riess et al. 2011).

Active galaxies: The discovery of quasars

- Quasars, or quasi-stellar objects (QSOs), were discovered by radio astronomers as small, "starlike," bright sources of radio emission (1950s).
- They were also identified by visible-light astronomers as stars with extremely peculiar spectra (1950s).
- The objects were reminiscent of the bright blue star-like galactic nuclei of some spiral galaxies discovered in the 1940s by Carl Seyfert (and earlier, Milt Humason), but no one noticed because no "nebulosity" was photographed in the surroundings of quasars.
- Maarten Schmidt was the first to realize in 1963 that the spectrum of one quasar, 3C 273, is actually fairly normal, but seen with $v_r = 47470$ km/s (Schmidt 1963). That is, $z = 0.1713$.

Spectrum of "nearby" quasar 3C 273



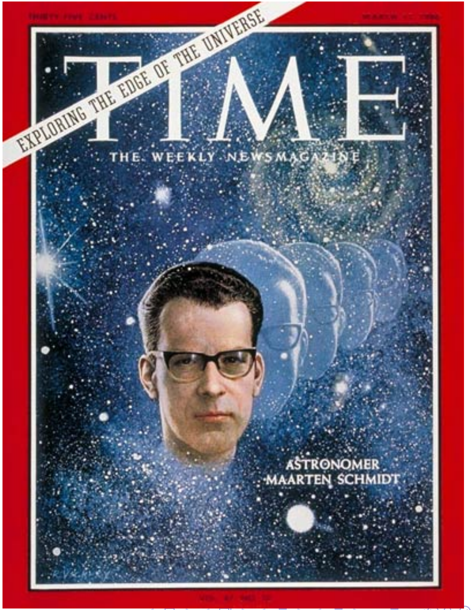
Discovery of quasars

Thus, from Hubble's Law, quasars are **very distant**. 3C 273 lies at $d = v_r/H_0 = 639.8$ Mpc.

Yet they are also **very luminous**. 3C 273 has a time-averaged luminosity of $10^{12} L_\odot$ (Greenstein & Schmidt 1964), almost $100\times$ that of the Milky Way and similar to that of the most luminous galaxies.

Observations show that quasars consist of a **very small** and bright core and a long thin jet. Radio data show that most of the brightness in 3C 273 is concentrated in a space < 3 pc in diameter!

Maarten Schmidt, 1966.



Discovery of quasars

The brightness of quasar cores is highly, and randomly, variable (i.e., they produce significant flares). 3C 273 can change in brightness by a factor of 3 in only a month.

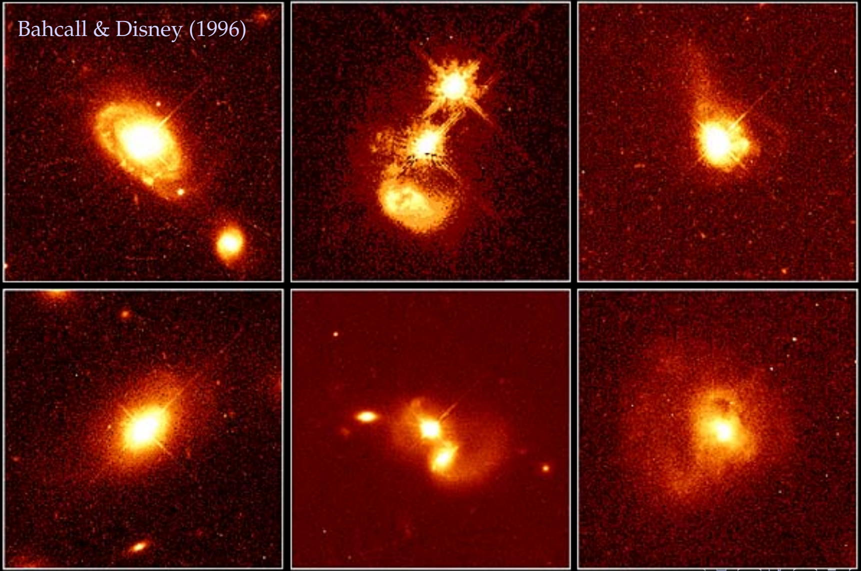
Enforcing causality (since $v < c$ for the motion of any material in the quasar) means that its power is actually concentrated in a region with a diameter no larger than one light-month, or

$$7.9 \times 10^{16} \text{ cm} = 5300 \text{ AU}$$

Some of the more violent quasars vary substantially in less than an hour (1 light-hour is 7.2 AU).

In the 1980s, the suspicions of most astronomers were confirmed when CCD images revealed that quasars are the nuclei of galaxies. Until good CCDs were available, the "fuzz" of the surrounding galaxy was lost in the glare of the quasar. This was shown by HST images in the 1990s (Bahcall et al. 1997).

Quasars and host galaxies



How are quasars powered?

To power a quasar, we need to generate $10^{12} L_\odot$ in a sphere with diameter $< 2.5 \times 10^{17} \approx 0.25$ ly. There are a few ways to do this:

Stellar power I 10^7 stars of maximum brightness $10^5 L_\odot$
Problem: Such stars only live ~ 1 Myr while the galaxies are ~ 10 Gyr old. We see so many QSOs that 10^6 is not a sufficient lifetime.

Stellar power II 10^{12} solar-type stars; their lifetimes are long enough to explain the number of quasars that we see.
Problem: The stars would typically be 0.5 AU apart, collide frequently, and quickly be destroyed. Also, a packed collection of stars totaling $10^{12} M_\odot$ has a Schwarzschild radius of 2 ly, or $8\times$ the size of our region. So a black hole would form.

Accretion power on a black hole Accretion of mass by a black hole might be a good solution if it does not drain the mass of the host galaxy too quickly.

How are quasars powered?

Accretion power of a black hole

Suppose a black hole in a QSO accretes a mass m. The energy released in the form of radiation is going to be

$$E = \eta m c^2$$

where $\eta \leq 1$ is the conversion efficiency. Note that $\eta \approx 0.1$ is considered reasonable. In this case,

$$L = \frac{dE}{dt} = \eta c^2 \frac{dm}{dt}$$
$$\frac{dm}{dt} = \frac{L}{\eta c^2} = 0.7\, M_\odot/\mathrm{yr} \quad \text{for} \quad \eta = 0.1, L = 10^{12} L_\odot$$

This is an infinitesimal drain on the total mass of a host galaxy, so accretion power seems feasible.