Cosmology

Fig. 1 A forest in Oregon

An early question about the nature of the universe is known as the Olbers's Paradox: why is it dark at night?

Olbers Paradox

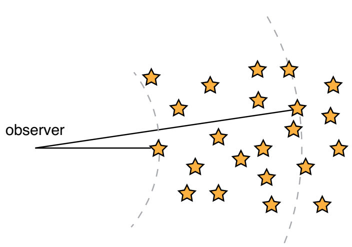

Fig. 2 If the universe is infinite, then there should be a star everywhere we look - why is it dark out?

Similarly, if we look in every direction, there should be a star there, ... eventually.

The assumptions:

1. The Universe is homogenous
2. The Universe is infinitely large
3. The Universe is infinitely old

Distances

Many different methods for measuring distances

Radar

How long for light to travel.

Example: Lunar Laser Ranging RetroReflector (LRRR) on the moon. Measures distance to

Fig. 3 Goddard's Laser Ranging Facility directing a laser (green beam)

Credit: Tom Zagwodzki/Goddard Space Flight Center

Parallax

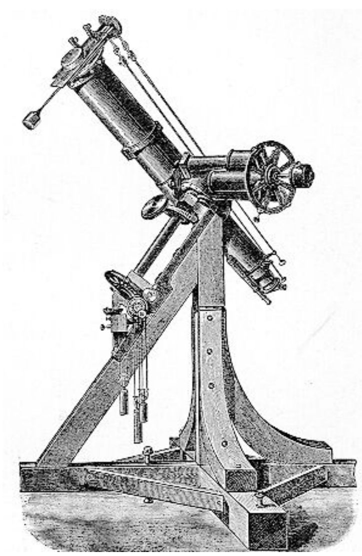

Fig. 4 Bessel's heliometer

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On earth: about 100 parsecs max distance.

HST Max distance 3,000 parsecs (10,000 ly)

Milky way is at least 30,000 parsecs in diameter.

(Andromda is about 780,000 parsecs away)

Standard Candles

The flux (measured brightness) of an object depends on two things: how far away it is and its luminosity:

$$F = \frac{L}{4\pi r^2} \quad (1)$$

where L is the luminosity and r is the distance between source and observer.

If we have a known value for L, then we can calculate r based on the measured flux.

Some well understood physical processes can help lock in a value for L

Cepheids - Variable stars

Period of brightness fluctuations is related to apparent magnitude, m.

If we know the distance to some nearby ones (from parallax), we can calibrate the relationship.

Max: 30,000,000 parsecs (~100 million ly)

Useful for objects in this galaxy, and a few nearby ones.

Type 1A Supernova

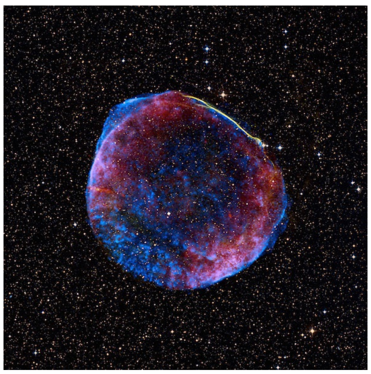


Fig. 5

X-ray: NASA/CXC/Rutgers/G.Cassam-Chena�, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

A white dwarf in a binary system can gain mass from the companion until it reaches a limit, producing an explosion. This is a supernova. The luminosity of the resulting explosion can be predicted.

Max: 1 billion ly

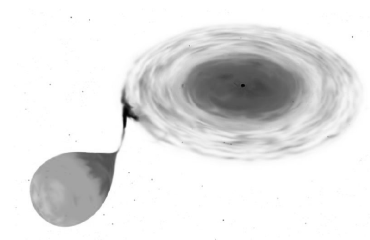


Fig. 6

STScI

Redshift

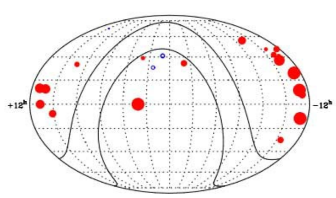


Fig. 7 Slipher's 1917 data on galaxies apparent velocities. (nearly all are moving away from us)

Slipher, galaxies, and cosmological velocity fields, John A. Peacock

Earlier 20th century observations of galactic spectra indicated red-shifted spectral lines for most. Vesto Slipher did the first measurements of redshift in galactic spectra. This suggested they were moving away from us.

Hubble's spectra from other galaxies.

Hubble was the first to correlate the redshifts to distance using Cepheid Variable stars outside the Milky Way.

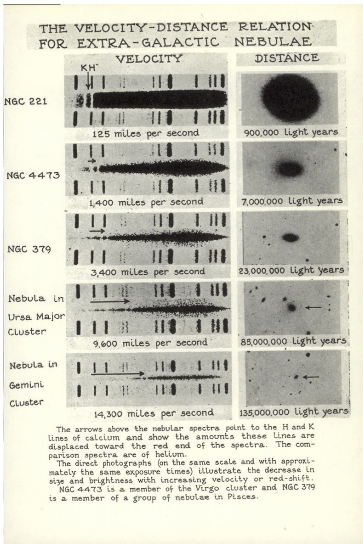


Fig. 8

Hubble - The Realm of the Nebulae

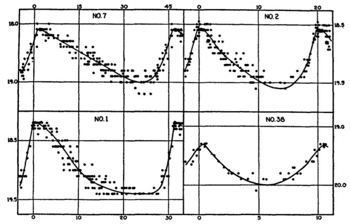


Fig. 9

Hubble's Velocity vs. Distance curve

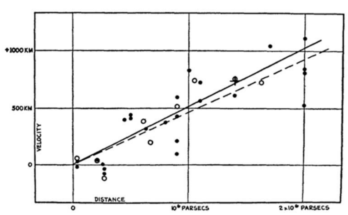


Fig. 10

From The Realm of the Nebulae

Hubble Parameter

The Hubble parameter is just the slope of the velocity-position data:

$$v = H_0 d \quad (2)$$

The value of H might depend on time, so we can call the Hubble constant the value it has today: $H_0 \equiv H(t_0)$

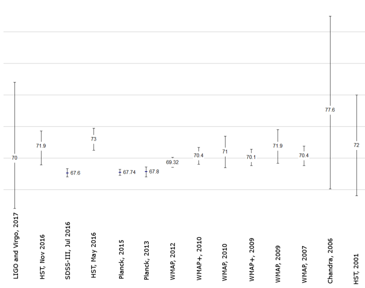


Fig. 11 Revisions to the Hubble Constant

The current value for H_0 is around 70.

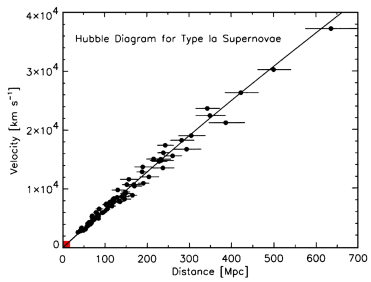


Fig. 12 A Hubble diagram using Type 1A supernova. (Hubble's original plot is contained in the small red square in the bottom left.)

10.1073/pnas.2536799100

Light

Define redshift as change in wavelength w.r.t wavelength at time of emission, e.

$$z \equiv \frac{\lambda_0 - \lambda_\mathrm{e}}{\lambda_\mathrm{e}} = \frac{\Delta\lambda}{\lambda_\mathrm{e}} \quad (3)$$

Expansion

If everything seems to moving away from everything else, then one possibility is that space is just getting bigger.

$$r(t) = a(t) r_0 \quad (4)$$

where r_0 is the separation at the current time, and $a(t)$ is a dimensionless function known as the scale factor.

Wavelength - scale factor relation

$$\frac{\lambda_e}{a(t_e)} = \frac{\lambda_0}{a(t_0)} \quad (5)$$

Thus,

$$1 + z = \frac{\lambda_e}{\lambda_0} = \frac{a(t_0)}{a(t_e)} = \frac{1}{a(t_e)} \quad (6)$$

Thus, observing a quasar with $z = 6.4$ means we are looking at it when the universe was

$$a(t_e) = \frac{1}{7.4} = 0.135 \quad (7)$$

times smaller.

Hubble Flow

The motion of galaxies as part of the expansion is called the **Hubble Flow**

This can be distinguished from the **peculiar velocity**, which would be for example, the motion of the Milky Way towards Andromeda.

Earlier times

If we run the 'film' backwards, then earlier in time, everything would have been much closer together.

Two options: either things would be more densely packed in the beginning, or maybe there was just less stuff.

Steady State Universe

Theories were proposed that suggested the universe was non changing in fundamental appearance.

Maybe the amount of matter was changing over time, so that the average density of the universe remained constant.

Big Bang

Another option was that the density was greater earlier in the history of the universe.

Also, the universe would have to be hotter too.

Big Bang Implications

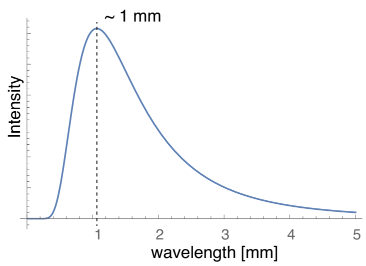


Fig. 13 Blackbody radiation for a temperature of around 3 K.

The amount of He-3 present in the universe can be used to figure out the temperatures necessary in the very early universe. Then based on the expansions rates, we can figure out a temperature that the universe should be at now.

Rough estimates predicted 3-5 K.

If the universe were a blackbody, this should be convertible to a peak wavelength.

Cosmic Microwave Background

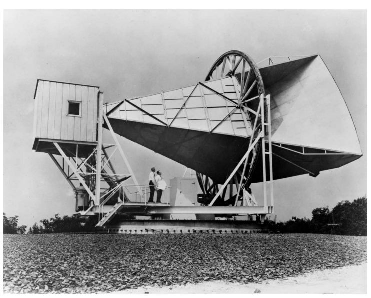


Fig. 14 The Holmdel Horn Antenna that Penzias and Wilson used to first measure the CMB.

By NASA - Great Images in NASA Description, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6463768

Two scientists working at Bell Labs kept recording a signal that they thought was noise - and couldn't get rid of not matter what they tried. They called some colleagues who were involved in microwave astronomy.

Isotropy/Anisotropy

Is it the same everywhere?

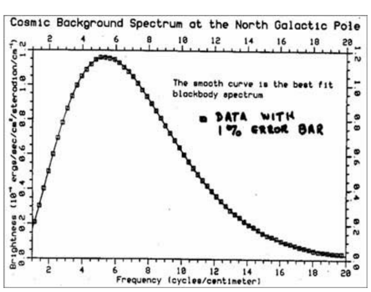
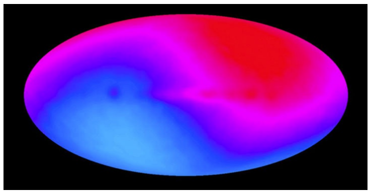


Fig. 15 Data from the first 9 Minutes of the COBE satellites mission.

Astrophysical Journal, Part 2 - Letters (ISSN 0004-637X), vol. 354, May 10, 1990, p. L37-L40

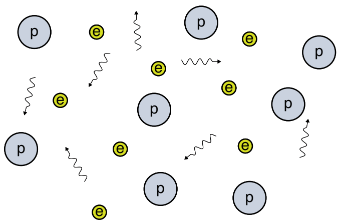


The CMB has a dipole anisotropy. This is likely due to the motion of the local group of galaxies compared to the rest of the visible universe, or the Hubble Flow.

Fig. 16 Dipole Anistropy

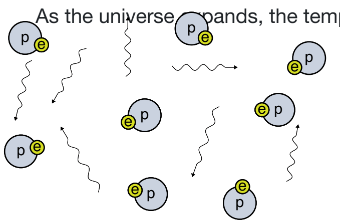
COBE dipole data

How to make a CMB?



- Start with a really hot dense beginning: $T \gg 10^4\ \mathrm{K}$. At these temperatures, baryonic matter will be completely ionized.
- Any photons will scatter of electrons and the universe will be opaque.
- A dense, hot, and opaque medium will produce blackbody radiation.

Fig. 17 The ionized, opaque universe before recombination



- As the universe expands, the temperature cools. Around $T \sim 3000\ \mathrm{K}$, the protons and free electrons combine to form neutral atoms.
- Now, the blackbody photons are free to stream throughout the universe.

Fig. 18 Transparent universe after recombination

Cooling of the CMB

The energy density of a photon gas:

$$u = \left(\frac{4\sigma}{c}\right) T^4 \quad (8)$$

and the pressure:

$$P = \frac{u}{3} \quad (9)$$

From the first law of thermodynamics.

$$dQ = dE + PdV \quad (10)$$

Since the universe is homogeneous and isotropic, we expect there to be no heat flow:$dQ = 0$.

Thus, we get:

$$\frac{dE}{dt} = -P(t)\frac{dV}{dt} \quad (11)$$

Substituting u and P from above, and taking derivatives, and simplifying:

$$\frac{1}{T}\frac{dT}{dt} = -\frac{1}{3V}\frac{dV}{dt} \quad (12)$$

since the volume of the universe is proportional to the scale factor cubed:

$$V(t) \propto a(t)^3 \quad (13)$$

we can write:

$$\frac{1}{T}\frac{dT}{dt} = -\frac{1}{a}\frac{da}{dt} \quad (14)$$

which can be reexpressed as:

$$\frac{d}{dt}(\ln T) = -\frac{d}{dt}(\ln a) \quad (15)$$

which implies:

$$T(t) \propto a(t)^{-1} \quad (16)$$

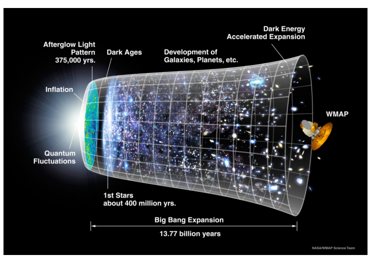


Fig. 19

NASA / WMAP Science Team

Olber's Paradox Resolution

The universe is not infinitely old.

Can't say how big it is, but only what we can see. (visible universe)