Comprendre l'infiniment grand: cosmology and large scales in the Universe



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We will talk about...

Cosmological principle, isotropy and homogeneity Distances: Hubble law and expansion of the Universe Abundances of light elements Background Cosmology in General Relativity Supernovae and Cosmic acceleration Cosmic Microwave Background Structure formation The Dark Universe



Some references

References:

Modern Cosmology, Dodelson

CMB physics and anisotropies: Hu & Dodelson 2002, Wayne Hu website, WMAP website: http://map.gsfc.nasa.gov/universe/

Dark Energy (Amendola & Tsujikawa)

Experiments: lambda.gfsc.nasa.gov

And references within the slides, which include work from several authors: L. Amendola, W. Hu, V. Springel, S. Dodelson, M.White, D.Weinberg, ...

Distances: https://cosmology.carnegiescience.edu/timeline https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/



What is the Universe made of?

Which forms of energy are in it? How do they evolve? What is the past, present and future of the Universe we live in? Do we have a standard picture, a cosmological standard model?



Cosmology

Study of the origin, evolution and content of the Universe.

NASA, ESA, G. Illingworth (UCO/Lick Observatory and University of California, Santa Cruz), and the HUDF09 Team Hubble Ultra Deep Field • Infrared STScI-PRC09-31 HST • WFC3/IR

At which scales and distances are we looking at?



"I apologize for the crudity of this presentation, but it's not on scale", E.L.B. - Back to the future

Very different scales



A journey through the cosmos



Hubble Space Telescope A journey through the cosmos

Hubble Space Telescope • ACS • WFC3



Hubble Frontier Field Abell 2744

Long-exposure Hubble Space Telescope image of massive galaxy cluster Abell 2744. It shows some of the faintest and youngest galaxies ever detected in space. Abell 2744, located in the constellation Sculptor [...] contains several hundred galaxies as they looked 3.5 billion years ago. [...]

Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

 $(7^{th} January 2014)$

STScI-PRC14-01a

<u>'The known Univers</u>

(developed by Americal Museum of Natural History)

Put things into perspective.

What do we actually know? How is it like to work in cosmology?



Not anymore a single astronomer

ACTpol **Bicep2 and SPT** Polarbear Planck -1 THE REAL REAL REAL REAL -----Cosmic MAXIMA BOOMerang DASI Background Imager 1 COBE WMAP MSAM ACBAR Sr. 1.2

2dF Galaxy Redshift Survey Sloan Digital Sky Survey







ESO

A 1

We know a lot of things about the Universe

V.Springel

We know a lot of things about the Universe

but also many things we don't know yet



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Cosmic Microwave Background

Structure formation

The Dark Universe

The cosmological principle

We are not privileged observers, in a special position in the universe.

The cosmological principle

We are not privileged observers, in a special position in the universe.

Homogeneity: at a given time, physical properties (ex. particle number density) are the same everywhere in space.



The cosmological principle

We are not privileged observers, in a special position in the universe.

Isotropy: physical quantities do not depend on the observation direction.



Two different concepts: but if it is isotropic to all observers, then it is also homogeneous.





Picture from Ned Wright's Cosmology Tutorial

Cosmological principle, isotropy and homogeneity

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Measuring distances

Distances are useful to measure intrinsic properties of objects in the Universe:

- Physical sizes of objects
- Masses of objects, given their orbital motion
- The laws that relate these properties
- Motion of stars through space
- Geometrical evolution of the Universe (expanding? Static? Distance is related to time)
- Age of the Universe



Stellar Parallax: apparent motion of a star with respect to more distant ones due to Earth motion around the Sun. Parallax angle.



Closer stars have larger parallaxes:



Distant stars have smaller parallaxes:



Parallax, first method to measure distances. The closer the star is, the larger is the parallax. Used for distances up to 100 pc, corresponding to angles of about 0.01 arcsec (not smaller).

Most stars even in our own galaxy are much further away than 1000 parsecs, since the Milky Way is about 30,000 parsecs across

Credit: R.Pogge, OSU



The top half of each frame shows the appearance of the sky as seen from the Earth (ignoring the Sun), and the bottom half shows a fixed view looking down from above onto the plane of the Earth's orbit around the Sun (the ecliptic).

The (red) star parallax motion is a reflection of Earth orbital motion.

It looks like it is moving with respect to distant stars.

The furtherst the star is the smaller is its 'parallax' motion. It can be used to obtain the distance: d (parsecs) = I/p (arcsec)

Credit: R.Pogge, OSU

1912: Henrietta Leavitt, Harvard College Observatory: found the key to measure the distance to stars much further away than 100 light years (> 33 pc). She identified more than 2400 variable stars (stars that change in brightness over a few hours/days/weeks) comparing photos taken at different times.



She looked for a relation between the brightness of a variable star and the length of its period.

Period of a variable star: the time to get brighter, dimmer and brighter again.

However, to measure the distance, you need to know the intrinsic brightness.







The outer layers of the star periodically expanding and contracting cause this pulsation.

Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

Cepheids as a distance measurement



The Blink Comparator has been one of the most valuable instruments ever invented for the science of astronomy. Two photographic images of the same star field are placed on the left and right sides of the instrument. The observer looks in the middle and lines up the two plates. The comparator then switches back and forth between the two plates, so that a star that is changing in brightness would be seen to rapidly flash on and off, while all the other stars



remain the same.

Blink comparator, Lowell Observatory. Image taken by Pretzelpaws

References:

http://sci.esa.int/education http://www.astronomynotes.com/ http://cosmology.carnegiescience.edu/ timeline/1912/blink-comparator

She used a particular kind of variable stars known as Cepheid variables, situated in the Small Magellanic Cloud (distant star cluster): all stars in the same cluster must be approximately the same distance from Earth. She identified 25 Cepheids in the cluster and plotted maximum brightness vs period. (Intrinsically) brighter stars have longer periods.



This was the key to all subsequent discoveries related to measurements of distances and of the expansion of the universe.



Leavitt did not know the distances to the Magellanic Clouds, so she could not tell what the actual value of the luminosity part of the relation was.

References:

http://sci.esa.int/education

Cepheids as a distance measurement



M = absolute magnitude P = period (days)

Cepheids as a distance measurement



References:

M = absolute magnitude P = period (days)

The procedure used later followed this set of steps:

- Measure the period of the star
- Use the Leavitt relation to determine the intrinsic brightness
- Measure how bright it actually appears
- Determine its distance (which can also be defined as the distance to the cluster galaxy in which it was found)

$$m-M=5\log d-5$$
 d = distance in parsec

How it is actually still currently done

Galaxies with known distance in which there are Chepeids: determine the absolute magnitude from its period, using Leavitt Law

Assume the absolute magnitude is the same everywhere

Use the Leavitt Law in galaxies of which we don't know the distance, which host both Chepeids and Supernovae to determine the distance

Use the relation between Supernova magnitude, distance and apparent magnitude to determine the expansion rate.

$$m_X^{
m SNe\,Ia} = 5 \log_{10} H_0 + \mu_0 - 5 a_X - 25$$

1912: Vesto Slipher obtained the first radial velocity of a spiral nebula (Andromeda galaxy) followed by many other measurements, establishing that recession velocities are a general property of spiral nebulae. The most distant ones were all showing redshift (velocity recession away from the observer). He was very careful and wondered about systematics or 'new physics'. This was then crucial when combined with Hubble distance measurements.



Vesto Melvin Slipher 1875-1969

Credit:	[1] https://cosmology.carnegiescience.edu/timeline/1929
	[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/



1914-1919: Harlow Shapley studied large groups of 'stars' called globular clusters and identified Cepheid variable stars in one of the nearest one.

He used the luminosity-period relation discovered by H Leavitt to recover their relative distances. In order to determine the absolute distance, he calibrated on Cepheids in our own galaxy, for which distances could be determined using parallax.

60-inch telescope

Credit:

Controversy about the location of globular clusters, whether they were in the Milky Way (Shapley) or that at least some of these nebulae were whole galaxies at much larger distances (Curtis). Debate in April 1920. The question was not solved there, but a few years later by Hubble.



Portrait of Harlow Shapley. Image courtesy of Harvard College Observatory

[1] <u>https://cosmology.carnegiescience.edu/timeline/1929</u>
[2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

Edwin Hubble was hired to work at Mount Wilson Observatory in 1919 (part of the Observatories of the Carnegie Institution of Washington)

The most pressing question of the day concerned the nature of the cloudy patches called nebulae. Most of Hubble's colleagues at Mount Wilson thought they were all in the Milky Way

He provided convincing evidence that at least some of them were well beyond the Milky Way



Edwin Hubble observing. Image courtesy of the Observatories of the Carnegie Institution for Science

Arrived at Mt. Wilson soon after the 100-inch reflecting telescope was completed. Hubble took many photographs of the same set of spiral nebulae (now called galaxies). Multiple images were needed in order to identify changes over time. On October 4, 1923, while comparing a photograph that he had just taken of the Andromeda galaxy with photos taken on previous nights, Hubble identified a Cepheid variable star. Comparing its apparent brightness with its actual brightness Hubble determined that it was 900,000 light years away.

Since Harlow Shapley had previously measured the distance across the Milky Way to be about 100,000 light years, the new findings clearly indicated that the Andromeda galaxy was far beyond the Milky Way. Later investigators found that there were two types of Cepheid variable stars, Andromeda was actually twice as far away—approximately 2 million light years. In subsequent decades, distances were measured to many other galaxies. Today, galaxies that are billions of light years distant have been observed.

1927: Lemaitre derived a linear relation between velocity and distance (including a Hubble constant)



Edwin Hubble observing. Image courtesy of the Observatories of the Carnegie Institution for Science

1929 paper by Hubble:



Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble was aware that a decade earlier astronomer Vesto Slipher had measured the recession velocity of several galaxies (and used his data [2]), finding a few that were approaching our Milky Way and several that were moving away at very high speeds. Hubble measured the period of Cepheids and absolute luminosity (L) (from Leavitt relation). Then from the apparent brightness (f=L/4 π td²) he obtained the distances d. He compared distances with the radial

velocities v measured by Slipher, obtaining an empirical relation between the two.

In 1929 Hubble published a paper that would lead to the realization that the universe was expanding.

$v = H_0 d$

Hubble's constant: $H_0=550 \text{ km/s/Mpc}$ (as measured at that time! Present measurements lead to about 70 km/s/Mpc)

Credit: [1] <u>https://cosmology.carnegiescience.edu/timeline/1929</u> [2]: https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

Age of the Universe



1929 paper by Hubble: http://www.pnas.org/content/15/3/168.full.pdf+html Discovery of the expanding universe was confirmed. By measuring the rate of expansion it was possible to determine the age of the universe by calculating when all the galaxies were in one place.

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble Diagram for Cepheids (flow-corrected)



Present measurements from SNae

Still using the Hubble relation between magnitude and distance, with a few adjustments.

Specifically, the distance estimator used in this analysis (and in most similar cosmological analyses) assumes that supernovae with identical color, shape and galactic environment have on average the same intrinsic luminosity for all redshifts. This hypothesis is quantified by a linear model, yielding a standardized distance modulus $\mu = 5 \log_{10}(d_L/10 \text{pc})$:

$$\mu = m_{\rm B}^{\star} - (M_B - \alpha \times X_1 + \beta \times C) \tag{4}$$

where m_B^{\star} corresponds to the observed peak magnitude in restframe *B* band and α , β and M_B are nuisance parameters in the distance estimate. Both the absolute magnitude M_B and β parameter were found to depend on host galaxy properties (Sullivan et al. 2011; Johansson et al. 2013b) although the mechanism is not fully understood. We use the C11 procedure to approxi-

Present measurements from SNae



Distance indicators



Expansion



We observe Hubble law: By vector addition,

v_B=Hd_B v_A=Hd_A

 $v_{BA} = v_B - v_A$ = H(d_B - d_A) = Hd_{BA}

Scale factor



One degree of freedom, function of time, that describes the background universe and how it expands.

Scale factor





Cosmological redshift



Redshift, all wavelengths are stretched with the expansion, shifted towards the 'redder' part of the spectrum (higher wavelength, proportional to the scale factor).

This is not the velocity at which galaxies move (peculiar velocities). Galaxies are on average at rest. They are gravitationally bound and do not expand. Space in between them expands.

Expansion and Hubble parameter



Derivative of the scale factor with respect to time

The expansion is related to the density content of the Universe and to the geometry of space time via the Friedmann equations (as we will see later).

Back in time

Back in time, the scale factor is smaller, the density and temperature increases as the content in it is compressed

Singularity at a = 0, about 13 billion years ago