Cosmology

Summer Term 2020, Lecture 03

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The Plan

Some remarks on the plan of the lectures —

- Aims and scope: This is an introductory lecture on cosmology. The focus is on the basic concepts and their motivation, leading up to the current "Λ-CDM standard cosmological model", i.e. a FLRW homogeneous, isotropic cosmological spacetime model filled with (i) baryonic matter, (ii) electromagnetic radiation, (iii) "dark energy" (Λ) and (iv) cold dark matter (CDM). We will discuss how observations together with a set of assumptions and their mathematical description motivate that standard cosmological model.
- Within that standard cosmological model, we will discuss the "thermal history of the universe"[see item and link on webpage], i.e. the "hot big bang scenario", giving a good picture of primordial nucleosynthesis, and the origin of the CMB. This is the standard canon of early cosmology, and one of the quite successful outcomes of cosmology. It uses what is known very well about the elementary particle physics and electromagnetic interactions from terrestial or laboratory experiments in the cosmological context. In leading order, the calculations are simple, and despite the simplicity of the approach, the results are in remarkably good agreement with observations.

- We will also discuss the arguments for an early cosmological inflationary scenario, and some basic ideas on pattern formation. Time permitting, we will look at some arguments for the temperature fluctuations of the CMB.
- To mention what is not part of the lectures: Pattern and structure formation is only mentioned at a very elementary level. Essentially, we only look at early cosmology, up to the stage of "recombination", i.e. the release of the CMB — with the exception of considering Λ, the dark energy term, which is an effect relating to later stage accelerated cosmic expansion. We don't look at any alternatives to the ΛCDM standard cosmological model or extensions, like potential approaches to quantum gravity, braneworld cosmologies etc. On the observational side, we don't consider astroparticle physics or gravitational lensing. Apart from mentioning their importance, there is nothing about complex computer simulations of the evolution of the Universe.
- It is also worth mentioning that the approach in these lectures is more influenced from the spacetime-geometric point of view, so that will form some part of the lectures, while what is needed from elementary particle physics is kept at a basic level.

- How we will proceed: In tis chapter, called “Observations”, we will first look at what can actually be observed (and how). Then we will look at distance determination from the observations, and the cosmic distance scales (the “cosmic distance ladder”). When translating the obervations into distances, some assumptions on the geometry (of space and time) have to made. We will start making the assumptions which were thought valid about 100 years ago — assuming the spacetime model of special relativity and Newtonian gravity. Redshift can then be interpreted as the relativistic Doppler effect, and as recession velocity. Some arguments for dark matter will also make their appearance. Some remarks on age determination and the distribution of chemical elements will also be made.
- Then we will see that the increase of recession velocity with distance together with the observed homeogeneity and isotropy of the matter distribution at very large scales doesn’t match very well with special relativity and Newtonian gravity, and take this as motivation to use general relativity as the spacetime concept for cosmology.

- In the following chapter, we will discuss some basics of general relativity, to then specialize to the homogeneous, isotropic cosmological spacetime models — the FLRW spacetime models. Concepts of distances will be considered in that framework, and we discuss how differing distance determination methods give rise rise to Λ, the cosmic constant or dark energy term.
- In the consequtive chapter(s), we will look at the thermal history of the early universe with its characteristic phases and phase transitions relating to elementary particle processes, and the resulting primordial nucleosynthesis and recombination, the latter leading to the CMB.
- As mentioned, towards the end of the course, we will look at early cosmological inflation, and hpoefully, take a glance at pattern formation and fluctuations in the CMB (“seed of pattern formation”, and their increase).

2.1 What can we observe?

The most important means of observation in astronomy is via the electromagnetic interaction, i.e. the detection of electromagnetic radiation. For some wavelength ranges, the Earth's atmospheres is intransparent.

- **Optical range of the spectrum:** $\lambda = 300...1000\,\mathrm{nm}$

  Earth's atmosphere is transparent in the optical spectral range. Scientific Earth-based telescopes are nowdays exclusively mirror telescopes. It is desirable to make the mirror, i.e. the light-collecting surface, as large as possible — this allows it to detect faint objects of low luminosity, and also increases the angular resolution. The technological advance in building large telescopes has been very rapid over the last 30 years (see next slide) — including active and adaptive optices, and the possibility to couple several optical telescopes together using computer generated imaging. Moreover — this concerns all observational methods — the advance in computer-assisted methods for signal filtering and analysis has been very important, allowing systematic, automatized searches for signals of certain signatures (e.g. in cosmology, far-away supernovae).

Limiting factors for the performance of optical telescopes on Earth come from clouds and fluctuations in the atmosphere, as well as scattered light — “light pollution”, i.e. light from artificial sources on the ground at night is increasingly a factor limiting the performance of telescopes. Therefore, high-performance telescopes are put in high and dry areas: E.g. mountain ranges in Chile and on Hawaii.

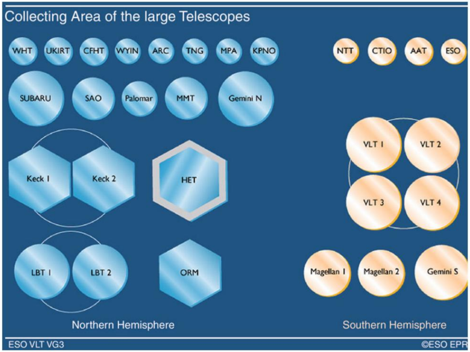


Fig. 11.1 The collecting area of large optical telescopes is displayed. Those in the Northern hemisphere are shown on the *left*, whereas southern telescopes are shown on the *right*. The joint collecting area of these telescopes has been increased by a large factor over the past two decades: only the telescopes shown in the *upper row* plus the 5-m Palomar telescope and the 6-m SAO were in operation before 1993. If, in addition, the parallel development of detectors is considered, it is easy to understand why observational astronomy is making such rapid progress. Credit: European Southern Observatory

P. Schneider, *Extragalactic Astronomy and Cosmology*, DOI 10.1007/978-3-642-54083-7__11, 573

The limitations due to atmospheric perturbations are absent for space-based telescopes (but there are other limitations, such as limitations in size and weight, and maintenance).

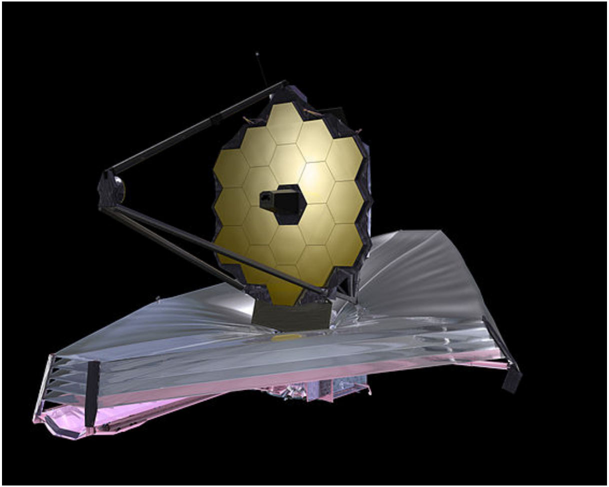
The most famous example is the **Hubble Space Telescope (HST)** which is in principle still operational — but will scratch Earth's atmosphere in 2024 and then be destroyed unless it would be rescued and the orbit lifted. The HST's Deep Field and Ultra Deep Field campaigns have been very important for cosmology.

Also in the optical range, the **Gaia space telescope** is important for exact distance determination and catalogization of stars and globular clusters in our galaxies and nearby galaxies — we come back to it a little bit later.

⋆ **Infrared range of the spectrum:** $\lambda = 1...300\,\mu$m

Earth's atmosphere is transparent in the near infrared range, $\lambda = 1...2.5\,\mu$m. Many new large Earth-based telescopes operate also in that range. It has advantages over the optical range because it is less susceptible to scattering by interstellar dust. In the range of larger wavelengths in the infrared band, the atmosphere is intransparent and observations have to be carried out using space probes. There have been a few: IRAS (1980s), ISO (1990), Spitzer Space Telescope (early 2000s), Herschel IR space telescope (2009-2013).

An upcoming project is the largest space based telescope, the **James Webb space telescope** (see next slide), operating in the near to middle infrared spectral range. The launch has been postponed a number of times due to financial and technological problems. It is presently set for 2021. It is considered important for cosmology since it can detect very distant objects at high redshift. One of the challenges for all telescopes operating in the infrared range is to shield it from heating by radiation, and the need of cooling the detectors.



An illustration of the James Webb space telescope in operational configuration, showing the radiation shields in the bottom part. Taken from Wikipedia.

⋆ **Microwave and radio spectral range:** $\lambda = 0.3\,\text{mm} \ldots 30\,\text{m}$

Earth's atmosphere is transparent in this wavelength range.

The 21 cm line of Hydrogen is important for detecting large aggregations of Hydrogen ("gas clouds") between galaxies.

Radio telescopes on far distant places on Earth can be combined to permit interferometric observations with very high angular resolution: Very long baseline interferometry.

The CMP is in the microwave range. For measuring it including its temperature fluctuations of $\delta T/T \simeq 10^{-5}$ precisely, space probes must be used — COBE, WMAP, Planck

⋆ **UV, X-ray and γ-ray spectral range:** $\lambda \leq 300\,\text{nm}$

The atmosphere is largely intransparent in that spectral range and observations have to carried out using space probes. There has been a history of them. The spectral and angular resolution in the X-ray and γ-ray range is very limited; in total, the significance of the higher frequency than UV range so far has been limited in cosmology, and we won't discuss this here any further.