Cosmology

Summer Term 2020, Lecture 02

Rainer Verch

Inst. f. Theoretische Physik
Universität Leipzig
06 April 2020

1.3 Some remarks on the historical development of cosmology

Cosmology developed together with astronomy: The question about the nature, distance, origin and evolution of luminous appearances in the night sky (and what the Earth, the Moon and the Sun have to do with it). In the course of development of astronomy and physics, some contributions have played a role in forming the concepts of cosmology — in particular about the questions: How large is the whole Universe (the world around us), what is it made of, what is its origin and its evolution.

The list compiled here does not claim accuracy in any sense of historical importance or completeness, it is mainly for illustrative purposes. I only list contributions that can be viewed as “scientific” from a modern point of view. The dates given vary in being life data or approximate dates of contributions being made. For some discussion relating to issues like “from myth to reason”, see e.g. the book by C. Sagan, *Cosmos*. Random House, 1980.

Claudius Ptolemy (100-170 AD)
Investigations on Mathematics and Physics, geocentric concept of the world: Planets, Sun and Moon move around the Earth (the center) in epicycles.

Nicolaus Copernicus (1473-1543)
Heliocentric concept of the world: Planets (including Earth) move on circular orbits around the Sun.

Galileo Galilei (1564-1642)
Law of free fall, physical concept of acceleration, method of comparison of theory and experiment (the foundation of physics as “science”), use of telescope for astronomical observations, discovery of Jupiter’s moons, Saturn’s rings and Sunspots.

Johannes Kepler (1571-1630)
Kepler’s laws of planetary motion on elliptical orbits around the sun, analysis to show consistency with Tycho Brahe’s observations. Observation of a supernova.

Isaac Newton (1642-1726)
Laws of mechanics, law of gravity, theory of light and its spectrum, optics, first mirror telescope, Newtonian spacetime, conjecture that an everywhere homogeneous matter distribution is unstable, theory of fixed stars.

William Herschel (1738-1822)
Construction of large mirror telescopes, discovery of the planet Uranus and of Saturn's moons, discovery of infrared radiation of the Sun, catalog and classification of "nebulae".

Heinrich Wilhelm Olbers (1758-1840)
Olber's paradoxon: In an infinite, eternal Universe with a homogeneous distribution of stars the sky must be bright and hot like the surface of the Sun.

Henrietta Swan Leavitt (1868-1921)
Catalog of variable stars, peridocity-luminosity relation for Cepheid-type variable stars

Ejnar Hertzsprung (1873-1967), **Henry Norris Russel** (1877-1957)
Hertzsprung-Russel-diagram of stellar evolution – emipirical spectrum-luminosity relation, distance determination of Cepheid-type stars in the Milky Way (our galaxy) [E.H.], evidence that luminous star atmospheres contain mainly hydrogen [H.N.R.]

Albert Einstein (1879-1955)
Special relativity, mass-energy equivalence, general relativity (1915)

Edwin Hubble (1889-1953)
Distance determination of the Andromeda nebula and discovering it as a galaxy outside of the Milky Way (1917), determining of redshifts of neighboring galaxies, interpretation as recession velocities – cosmic expansion (1927, previously found by Lemaître)

$\sim$ **1922. . . 37: A. Friedmann, G. Lemaître, H. Robertson, A.G. Walker**
Homogeneous, isotropic cosmological spacetime models **(FLRW)** as solutions to Einstein's equations of gravity, cosmic expansion means finite past lifetime of the Universe, extreme high energy-density phase towards initial time.

Remark

The FLRW spacetime models are those the present-day standard models of cosmology are based on. Their discovery stands for the beginning of the spacetime-geometric approach to cosmology mentioned in lecture 01. In particular, Robertson's article "Relativistic cosmology", Rev. Mod. Phys. **5**, 62-90, 1933, has been influential in this respect. However, at the time of their appearance, the FLRW spacetime models were not generally accepted as a theoretical description of the Universe — we will come back to this later.

from $\sim$ 1924...

Schrödinger, Heisenberg, Dirac, Pauli, Fermi, Landau, Bethe, v. Weizsäcker, Chandrasekar, Feynman, Schwinger, Tomonaga, Gamov, Sakharov, Wheeler, Zeldovich, Gell-Mann, Salam, Weinberg, Higgs, Brout, Englert,...and many others

Development of quantum mechanics, quantum field theory, elementary particle physics and application to the processes in luminous stars, theory of stellar evolution (fusion processes), final states of stars, role of supernovae in generating heavier elements.

$\sim$ 1948: Gamov et al.

"Hot big bang" szenario in early phase of cosmology, prediction of CMB

$\sim$ 1964...65: Penzias and Wilson

Discovery of the CMB at 2.7 K

The discovery of the CMB is very significant — it made the FLRW cosmological models and the "hot big bang" the preferred scenario over alternative cosmological models. It also establishes the beginning of the elementary physics approach to early cosmology.

Zwicky ($\sim$ 1933), Rubin et al. ($\sim$ 1970s)
Observations of galaxies and galaxy clusters indicate they must have more mass than is electromagnetically visible: “dark matter”

from $\sim$ 1963...
Schmidt, Zeldovich, Rees and many others...
Discovery of quasars and active galactive nuclei, indication for supermassive black holes at the cores of galaxies, important benchmarks for cosmic evolution.

from $\sim$ 1970...
Peebles, Wagoner and many others...
Theory on the formation and distribution of elements (nucleosynthesis) from the “hot big bang” scenario, and on structure formation in the Universe out of density fluctuations in the “hot big bang” phase.

∼ 1982
Guth, Linde, Starobinski, Steinhardt et al.
Theory of phase of "early inflationary cosmological expansion" before the "hot big bang" era. Presently the favoured scenario in early cosmology.

since ∼ 1990s
Discovery of exoplanets (so far > 4000 known)

∼ 1980...1990
Chibisov, Mukhanov, Feldman, Brandenberger, Bardeen and others
Theory of quantum cosmological/matter fluctuations as the seeds for the density fluctuations in the early universe, leading (together with inflation) to small temperature anisotropies in the CMB.

from ∼ 1989: Geller, Huachra, Sloan et al.
"redshift surveys" to map the Universe at very large scale: Discovery of large galaxy formations arranged in thin "bands" or "walls" with "grand voids" inbetween, significant inhomogenities at 5% of the length scale of the observable Universe.

from $\sim$ 1993: Smoot, Mather and many others
COBE space probe (1993), WMAP space probe (2003),
Planck space probe (2009)
Precise measurement of CMB and its anisotropies. Observations support the "hot big bang" and inflationary scenario, and quantum fluctuations as seeds for density perturbations.

since $\sim$ 1998: Riess, Perlmutter et al.
High-z Supernova Search Team and Supernova Cosmology Project
Observations of the most distant Type Ia supernovae show a difference in luminosity/red shift distances, indicating a late-era cosmic expansion whose origin is termed "dark energy" in FLRW cosmological models.

$\sim$ 2003...2004
Hubble ultra deep field observation campaign
Observation of the most distant galaxies with the Hubble space telescope shows they must have formed more than $1.3 \cdot 10^{10}$ years ago, and are young galaxies with a high creation rate of stars.

from $\sim$ early 2000s: Springel, Vogelsberger, Primack and many others
Complex computer simulations modelling the structure of the Universe from early phase density perturbations

- Millenium 1 (2005)
- Millenium 2 (2009)
- Millenium XXL (2010)
- Bolshoi (2010)
- Illustris (2011...14)
- IllustrisTNG (2015...)

The results indicate that dark matter is needed to obtain the large-scale late-time structure in the Universe, as we observe it, at the observed time scales. Large band-like structures of galaxy formations with big voids and supermassive black holes are generically produced in the simulations.

$\sim$ 2015: Weiss, Barish, Thorne and many others
Direct measurement of gravitational waves from the merger of two stellar-size black holes by the LIGO interferometers

$\sim$ 2019
Radio image of a supermassive black hole in the core of the galaxy M87