Astrophysics V Observational Cosmology

Sheet 5: Assignments

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Exercise 1 : Evolution of the Universe

Today the Universe appears to be dominated by dark energy, as the expansion of the Universe is accelerating. About 3/4 of the total mass-energy of the universe is dark energy, and the remaining quarter is virtually all matter (dark matter and baryonic matter). The radiation in the universe is a small fraction, which is mostly the cosmic microwave background (CMB).

However, it was not always this way. In the early stages of the Big Bang, most of the energy was in the form of radiation which was the dominant cause of the expansion of the universe. Later on, due to the cooling caused by the expansion, the roles of mass and radiation changed and the universe entered a mass-dominated era.

Suppose that we are living in a flat ΛCDM Universe, with the cosmological parameters being the most probable ones obtained through the CMB measurements of the Planck satellite in 2015 ($H_0 = 67.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}, \Omega_\mathrm{m} = 0.307$). Using the cosmology class of the nbodykit package [1] [2] [3] :

a) plot the evolution of the radiation density, matter density, and dark energy density as a function of proper time

b) find the phase transition epochs

c) plot the growth of the size (represented by the scale factor) of the Universe and analyze the evolution for two different time ranges : $t \in [10, 1000]$ years and $t \in [10^6, 10^8]$ years.

1. https://nbodykit.readthedocs.io/en/latest/getting-started/cosmology.html
2. https://classylss.readthedocs.io/en/stable/api/classylss.binding.html#classylss.binding.Background
3. https://classylss.readthedocs.io/en/stable/examples.html

d) plot the density parameter for the three components as the function of scale factor.

Exercise 2 : Distances in the Universe

In cosmology (or to be more specific, cosmography, the measurement of the Universe) there are many ways to specify the distance between two points, because in the expanding Universe, the distances between comoving objects are constantly changing, and Earth-bound observers look back in time as they look out in distance. The unifying aspect is that all distance measurements are related to the separation between events on radial null trajectories, i.e., trajectories of photons which terminate at the observer. Assume, initially, that we are living in a flat ΛCDM Universe, with the cosmological parameters being the most probable ones obtained through the CMB measurements of the Planck satellite in 2015 ($H_0 = 67.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}, \Omega_\mathrm{m} = 0.307$).

a) Using the `numpy` [4] and `scipy` packages [5], implement the formulas for the comoving distance, luminosity distance, angular diameter distance and look-back distance. Plot the distances as functions of redshift and check your results with the `cosmology` class of the `astropy` package [6].

b) Change the Ω and the Hubble parameters and check the impact on the distances.

c) Type Ia supernova (SNIa) is one type of the so-called "standard candle", for measuring luminosity distances in the Universe. Indeed, it is from supernovae measurements that we know the Universe is expanding at an accelerating rate, which is mostly commonly explained by the dark energy hypothesis. Implement the formulas for the modified cosmological model and plot the relationship between luminosity distance and redshift in different dark energy models (say, $\Omega_\Lambda = \{0.6, 0.693, 0.8\}$, and $w = \{-0.9, -1.0, -1.1\}$, where w is the dark energy equation of state).

d) Apart from SNIa, Baryon Acoustic Oscillation (BAO) provides another way to measure the geometry of the Universe. Indeed BAO is known as the "standard ruler", for measuring angular diameter distances and the Hubble parameter. Using the same dark energy models above, plot the evolution of angular diameter distance.

4. https://numpy.org/doc/1.18/
5. https://docs.scipy.org/doc/scipy-1.4.1/reference/
6. http://docs.astropy.org/en/stable/cosmology