COSMOLOGY

Introduction

Cosmology is the study of the universe, the structure and evolution on large scales. The larger the scales, generally, the study becomes easier. The main reason being that at large enough scales gravity is the dominant force. Although electromagnetism, for example, is a stronger force, large-scale objects are neutral. If gravity is the dominant force, then general relativity (GR) governs the evolution of the universe.

There is even more simplification, as we shall see, if one works at scales smaller than the Hubble radius (~ horizon for std. cosmology) then Newtonian gravity becomes an excellent approximation. The expanding universe only calls for a redefinition of momentum and coordinates.

It's very important as we go along to have always order of magnitude estimates of everything we do. The basic units we use get determined by the characteristic sizes and energies that show up at different stages of the universe's evolution. Some of the astronomical ones that you should know right away are e.g.

Object	Mass (g.)	Size (cm.)
Sun	$1M_\odot = 2\times10^{33}$	7×10^{10}
Galaxy	$\sim10^{11}M_\odot = 2\times10^{44}$	~ 10 kpc $\sim 3\times10^{22}$
cluster of Galaxies	$\sim10^{14}M_\odot = 2\times10^{47}$	$\lesssim$ few Mpc $\sim 10^{25}$
Universe	$\sim \rho_{crit}\times\underset{\text{radius}}{\text{Hubble}} \sim 8\times10^{55}$	Hubble radius $= H_0^{-1}c = 3000$ Mpc $\sim 10^{28}$

$$\rho_{crit} = 3H_0^2/8\pi G \sim 2\times10^{-29}\ g/cm^3 \sim 28\times10^{10}(M_\odot/h)/(Mpc/h)^3$$

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A parsec (pc) is the distance one has to put a star in order to have a paralax of 1 arc sec.

The basics of standard cosmology can be summonized in a few simple ideas (backed up by impressive amounts of observation and theoretical work):

- The mass (and energy) distibation are very close to homogeneous and isotropic on large enough scales (on average))

- The universe is expanding, with a mean velocity between objects given by the Hubble law:

$$v(r) = H_0 \, r \qquad H_0 \equiv 100 \, \underset{\uparrow}{h} \, \frac{km}{s} \frac{1}{Mpc}$$

$h \sim 0.7$, as we will discuss.

- The dynamics of the expanding universe obeys GR (local physics is the same everywhere and at all times)

- The universe expanded from a hot dense state where energy was dominated by thermal black body radiation.

We will explore this in great detail in the next few weaks.

[show thermal history chart]

The number of things that can be worked out and contrasted (succesfully!) with observations is really impressive.

Homogeneity and Isotropy

Homogeneity (H) : invariance under translations
Isotropy (I) : " " rotations

Obviously, such concepts can only hold in some average sense in the clumpy Universe with stars, galaxies, etc. We shall come back to this later in greater detail, but H & I is meant in a statistical sense when one averages over large distances.

This notion already introduces a set of privileged observers, called comoving observers, which roughly speaking "move with the expansion of the universe", i.e. they are locally at rest with respect to nearby material (and thus measure zero momentum density at their location).

Note that comoving observers are inertial observers, but not any inertial observer is comoving. (For example, doing a boost will generate obviously velocity with respect to local matter.

That the universe is H & I translates into the statement that comoving observers see invariance under translation and rotations of the large-scale properties of the universe. In particular, the average density is a function of cosmic time alone:

$$\bar{\rho} = \bar{\rho}(t)$$

[Doing a boost, for example one can redefine $t, \bar{x}$ so that $\bar{\rho} = \bar{\rho}(\bar{x}', t')$, in that sense those will not be comoving obs., also, a boost even less complicated than that will create blueshifts instead of the simplest form of Hubble's law, see below]

Observational "proof" that the universe is isotropic is important, since unless we think we are at the center of the Universe isotropy about 2 points imply homogeneity.

However, if we relax isotropy, in pple there are a large class of models that are anisotropic and homogeneous (the Bianchi models). While H&I completely determines the metric in GR up to sign of curvature, in the case of Bianchi models, there are much more structure involved. The simplest perhaps are models where expansion rates along different cartesian directions is different (anisotropy) but these directions are the same everywhere in space (homogeneity). We will not consider this further as there is no evidence for this type of models.

The evidence for isotropy is pretty solid:

i) isotropic distribution of galaxies at large angular scales in the sky

ii) same for radio sources, or x-ray background

iii) the most impressive of all, the isotropy of the cosmic microwave background (CMB), which apart from a dipole pattern due to our motion, implies a constant blackbody temperature of about 11 parts in 10^6.

The value measured by COBE is

$$T_0 = 2.72528 \pm 0.00065\ {}^{\circ}K$$ from 0.5 to 5 mm in wavelength.

[Show COBE results]

The observational evidence leads to the so-called Cosmological Principle: the universe is homogeneous and isotropic.

Expansion: Hubble's law

In 1929, Hubble discovered that most galaxies were receding with respect to the Milky way with a law

$$v(r) = H_0 r$$

He used cepheids variable stars to infer distances (and that led to a problem, since $H_0 \sim 500 \frac{km}{s} /Mpc$ he found corresponds to an age of order 2 Gyr, in conflict with other data, but this was due to a misunderstanding of local and distant cepheids with different period-luminosity relation). Nowadays things are determined extremely well ($\lesssim 10\%$) with $H_0 \simeq 72 \frac{km}{s} /Mpc$

[show Key project results]

Note that $\bar{v} \propto \bar{r}$ is compatible with the cosmological pple, any observer will measure the same form since $\bar{v}_1 - \bar{v}_2 \propto \bar{r}_1 - \bar{r}_2$