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FACULTAD DE CIENCIAS EXACTAS Y NATURALES

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Baryon acoustic oscillations in the dark matter halos in the SDSS

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CAPÍTULO 1

Introduction

In the standard model of cosmology the universe was born in a big bang, an explosion that produced an expanding, isotropic and homogeneous Universe. From observations it has been found that this expansion is currently accelerating with time (Hamuy et al.,1996).

There are several components of the matter-energy content of the universe, dark and baryonic matter, radiation and dark energy. According to recent estimations DEF, the last one accounts for around 70 % of this content and is responsible for the accelerated expansion of the universe. The baryonic acoustic oscillations allows to study the nature of this expansion as it will be explained.

In the early universe the dark matter (DM) formed density fluctuations, causing baryonic matter to be unstable against gravitational perturbations. At this stage in the evolution of the universe the temperature was very high, allowing a coupling between baryonic matter and radiation through Thomson scattering. So the increase of baryonic matter in the DM density fluctuations not only caused an increase in density, but also radiation pressure against collapse. Therefore, an expanding wave centered in the fluctuation is caused because of the radiation pressure. This wave is the baryonic acoustic oscillation (BAO) (Hu and Sugiyama, 1996; Eisenstein and Hu, 1998).

Nevertheless, it is necessary to consider that the universe is expanding and this results in a temperature decrease. Therefore, when temperature is low enough the baryonic matter and radiation decoupled, making BAO to stop expanding and leaving an imprint in the matter distribution. The distance that a BAO could have travelled by the time of decoupling is called sound horizon. This scale has been measured in the Cosmic Microwave Background as $146{,}8 \pm 1{,}8$Mpc, ([?]).

Since BAO do not change in size after decoupling they can be used as a standard ruler. They allow to measure the Hubble parameter and angular diameter distance as a function of z, and this way to measure the rate of expansion at different times during the evolution of the universe. Hence, BAO is key to constraint dark energy parameters.

A way to observe the imprint let by BAO is through the 2D point correlation function or the power spectrum that is its fourier pair, ([?], [?]). A peak due to the BAO appears in the correlation function (see figure ??) but there are several issues to take into consideration. There is a bias between baryonic and dark matter distribution ([?]) and hence in their correlation functions. This bias plays an important role when observational data is being studied. A method proposed in such cases is suggested in ([?]). Moreover, the non-linear clustering smear out the BAO imprint causing a broadening of the peak (Crocce and Scoccimarro, 2008). These, among other problems, have to be taken into account when BAO are studied.

Observational studies of baryonic acoustic oscillations have been done in several previous works such as [?], [?], [?], [?] . Measurements of baryonic acoustic oscillations on simulations have also been done in these works by [?], [?], [?], [?]. And theoretical studies of baryonic acoustic oscillation using non linear theory have been realized in [?], [?], [?], [?] .

In the present work, we plan to do a comparison between the power spectrum estimated from numerical cosmological simulations and the one obtained from observations of the Sloan Digital Sky Survey (SDSS). The method to construct the power spectrum is shown in section ??.2. The method to obtain the dark matter density field for observations is explained in section ??.3. In both cases, observations and numerical cosmological simulations, the BAO peak will be studied, but what are the changes of the BAO's properties with changing the scale of the tracer halo population? is there any change in the position peak? is there any change in the width peak? or, is there a damping in the oscillations caused by BAO in the power spectrum? In general, the question we want to answer is: Is there any dependence in the width and amplitude of the BAO signal with the tracer halo population? Answering this questions will lead not only to profound understanding of the physics of BAO but a better understanding of the accelerated expansion of the universe that still has so many questions to be answered.

1.1. Baryonic acoustic oscillations

CAPÍTULO 2

Cosmological Background

Cosmology is the branch of physics that studies the Universe as a whole, therefore, it attempts to explain the observed structure of the Universe, at least, at big scales. Hence, a coarse grained approximation is mandatory, this is, several approximations are necessary in the endeavour of such a task. In this search, two major points are considered. The first one is the cosmological principle, it assumes that on sufficiently large scales the Universe can be considered homogeneous and isotropic. Until now, observations have agreed with this asseveration.

Furthermore, Einstein field equations serve as a relative simple mathematical tool to study the Universe at big scales. From them, Friedmman equations provide a theoretical framework for a big bang and posterior universe expansion. A standard model in cosmology is λCDM, where additionally to an expanding universe, there is a dark energy component that accelerates its expansion. This is precisely the framework that is going to be used in this work.

In this chapter, several basic concepts are going to be introduce to finally lead to bayronic acoustic oscillations (BAO).

2.1. Robertson Walker Metric

As was mentioned before, observations of the Universe at big scales show that it is homogenous and isotropic. This idea is also reinforced by the cosmic microwave background radiation

(CMB), since it appears to have inhomogeneties only at very small scales. Nevertheless, it can not be proven and it is taken as a postulate.

- Cosmological principle: *The Universe is homogeneous and isotropic at big scales.*

  In this context, homogeneous is understood as the independence of the place where a reference system is defined, i.e., the structure of the Universe observed is the same no matter the reference system used. On the other hand, isotropy stablishes that regardless of the direction chosen, the same structure is going to be observed. Then, we are dealing with traslational and rotational symmetry.

  These characteristics are observed on mega parsec scales, i.e., big scales. However, this is only valid for the actual epoch, the scale changes with time due to the expansion of the Universe.

- Weyl postulate : *Establishes that the geodesics, world lines of galaxies, do not intersect except in a singular point in a finite or infinite point, past.*

  This one defines a set of observers that move along the geodesics. The interception point allows to synchronize watches among different observers, defining a cosmic time. Therefore, the distance between galaxies can be measured at the same cosmic time.

There is another important fact to take into account before speaking of a metric, the Universe is expanding. It was due to a research on near galaxies performed by Edwin Hubble, that a redshift was found in most of the galaxies, i.e., they are moving away from us. Considering this movement, one could conclude we are in the center of the expansion. But this conclusion is wrong, since the expansion Hubble law is valid independently where the coordinate system is defined.

A metric that satisfies homogenity and isotropy and additionally contains a term that corresponds to the expansion, is the Friedmann–Lemaître–Robertson–Walker metric. It is defined in general terms as $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$, where $g_{\mu\nu}$ is the metric tensor and uses coordinates $x^\alpha = \{ct, x, y, z\}$. The metric tensor takes the next form $g_{\mu\nu} = diag\{1, -\frac{a^2}{1-k^2} - a^2 r^2, -a^2 r^2 \sin^2\theta\}$, and the metric is finally

$$ds^2 = c^2 dt^2 - a(t)^2 \left[\frac{d^2 r}{1 - Kr^2} + r^2(d^2\theta + \sin^2\theta d^2\phi) \right] \tag{2.1}$$

The term $a(t)$ is the scale factor, it describes how the relative distance between two fundamental observers changes with time. The term K is the curvature constant for the actual time and defines the Universe geometry. When $K = 0$ an euclidean metric is recovered leading to a flat universe expanding indefinitly. If $K = 1$ the Universe would be described by a spherical geometry and it would collapse because of its energy matter content. And finally, $K = -1$ corresponds to a hyperbolic geometry where the Universe would be in accelerated expansion.

One important aspect to consider is that the geometry depends on the total energy matter content, Ω_o. This can be concluded from te definition of the curvature constant $K = H_o^2(\Omega_o - 1)/c^2$.

Different cosmologies are shown in the figure 2.1.

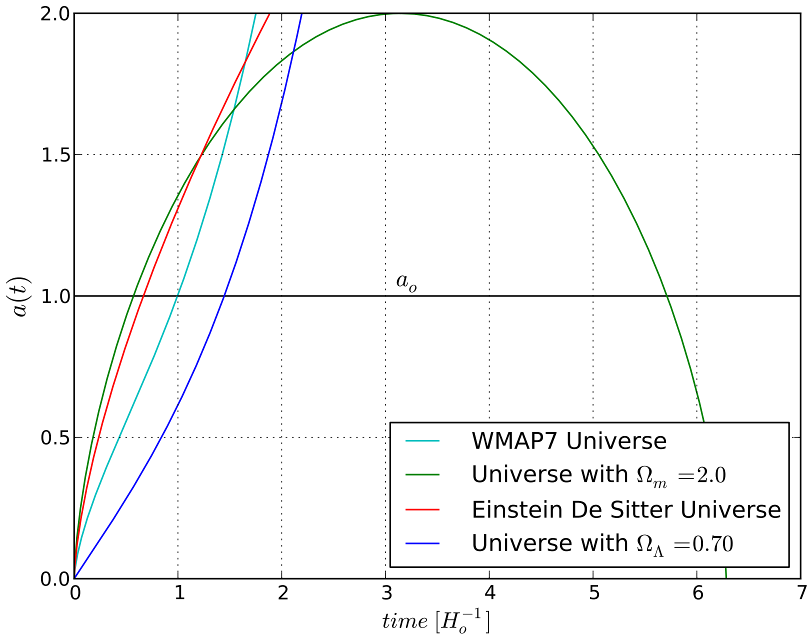

Figura 2.1: Scale factor as a time function. The Universe expansion for different density contributions. A closed Universe is obtained when $\Omega_m = \Omega_o > 1$. Also, the WMAP7 parameters show an acelerated expansion.

2.2. Hilbert Einstein field equation

At big scales, the most important fundamental interaction is the gravitational. Hence, the theory of general relativity (TGR) is an essential tool in the study of the cosmos.

At smaller scales, the Newtonian gravitational theory is valid, where, the Poisson equation offers a relation between the second derivative of the field and the source of the field

$$\nabla^2\Phi = 4\pi G\rho$$

this equation is obtained from TGR for low velocities and a weak gravitational field ($\Phi/c^2 << 1$). A key equation of TGR is the Hilbert-Einstein field equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{2.2}$$

a 6 independent component tensorial equation. The first term of the left is Ricci tensor (second derivatives of the metric tensor). The second one is the scalar curvature that

2.3. Friedmann equations

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CAPÍTULO 3

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3.2.2. Bound density maximum

3.3. Correlation functions in cosmological simulations

3.4. Power spectrum in cosmological simulations