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Oscilaciones Bariónicas Acústicas en Universos con Curvatura

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Fecha de entrega

Agradecimientos

Incluir los agradecimientos, si procede.

Contents

Índice de figures

List of Tables

Resumen

Escriba aquí un resumen de la memoria en castellano que contenga entre 100 y 300 palabras. Las palabras clave serán entre 3 y 6.

Palabras clave: palabra clave 1; palabra clave 2; palabra clave 3; palabra clave 4

Abstract

Insert here the abstract of the report with an extension between 100 and 300 words.

Keywords: keyword1; keyword2; keyword3; keyword4

CHAPTER 1

Introduction

1.1. The Hot Big Bang model

The most accepted model for the origin of the universe is the Big Bang model, which surprisingly to some conveys no "bang", but the sudden existence of all the matter in the universe, in the shortest of times, in the smallest of spaces, about 13.8 billion years ago. After an unthinkably small interval of time, the universe began a short period of rapid expansion known as *cosmic inflation*, in which the universe grew by a factor 10^{27} in a mere 10^{-33} seconds. This inflation is thought to be due to the inflaton, a quantum scalar field theory. It is theorized that it is the inflaton's vaccuum energy what caused the universe to expand as greatly.

After this inflation phase, the universe cooled enough for what is known as the Quark-Gluon plasma to form. In this state, temperatures were high enough as to consider relativistic the random motion of the particles in it. After some cooling due to cosmic expansion, the combination between quarks to form hadrons was allowed, leading to what is known as the hadronic epoch. However, due to the short mean free path of the photons the universe is still opaque to electromagnetic radiation.

As the universe kept expanding the densities and the temperatures cooled, the existence of atoms was starting to be allowed, the He^+ and H atoms. This period would finish at the universe age of $380,000$ years, moment known as recombination. Though the name 'recombination' implies the fact that the universe used to be 'combined' and then ceased to be so, it just comes from the fact that recombination was theorized before the Big Bang theory was thought of.

As soon as recombination ends, the excited electrons which are now orbiting neutral atoms, fall to a lower energy state, thus emmitting photons in great densities. This emmision is known as the Cosmic Microwave Background (CMB) and is the oldest direct measurement we can take of the unvierse.

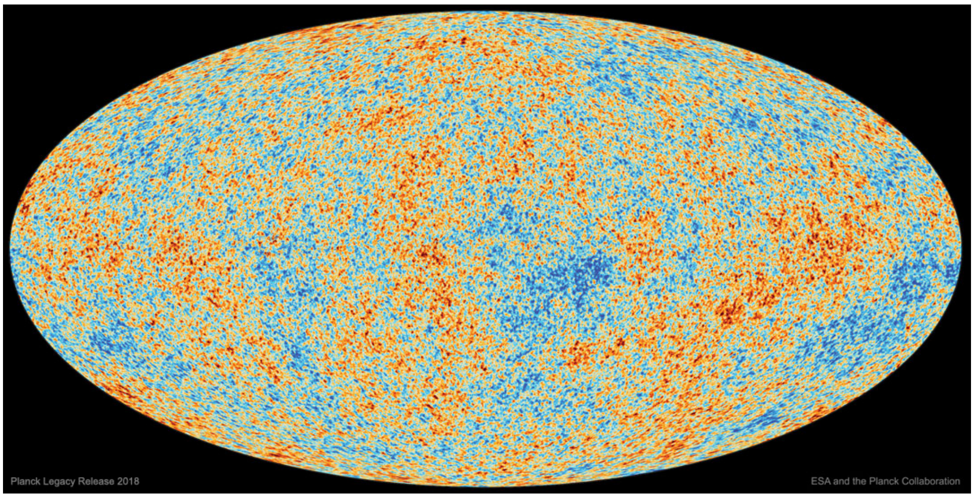

Figura 1.1: The CMB as seen by Space-based Observatory Planck

1.2. Cosmic Microwave Background

We see in the figure 1.1 the CMB as observed by the Planck colaboration [2]. The radiaton we observe is the photons that were emmitted about 13.3 million years ago. Since the CMB appears as a result of the thermal photons emitted by the electrons in the primordial plasma, it offers great insight into what the plasma looked like, and the way it behaved.

As the name suggests, the CMB radiation consists of wavelengths of radiation of the order of micro meters. In fact, one can measure the associated temperature to this wavelength to be 2.7260K[7] with some fluctuations of approximately 0.0013 K. However, this is definitely not the temperature of the plasma before recombination. It was in fact, about $2725K$, or ≈ 1000 times higher. This is due to the process of *cosmological redshift*, which will be explained later on.

A natural question arises: How does this not break the cosmological principle? (i.e. the universe is isotropic and homogenous, meaning it is the same in every direction and at every point in space, respectively)

These fluctuations may be explained by the microscopic quantum oscillatios of the different fields that make up matter before and during cosmic inflation. The details of the mechanism that allows a particle to be explained as a field goes way beyond the scope of this paper, so it suffices to just mention the fact that at high enough energies, the concept of particle loses its meaning and it needs to be modeled as a constantly fluctuating field in all of space.

Thus, the CMB becomes crucial in explaining the large scale structure of the universe, since the photons that decoupled from the plasma at recombination wasted more energy leaving denser regions behind losing thermal energy in the process.

1.3. Baryon Acoustic Oscillations

Before recombination, all matter was coupled into the same fluid which we have called the primordial plasma. The particles in the plasma interacted primarily with one another through gravity and electromagnetism, depending on the type of matter considered.

As already mentioned, matter was not distributed homogenously so at some point in time before recombination one could find 'lumps' of dark and baryonic (standard) matter. Combining the gravitational attraction between dark and baryonic matter with itself and with one another, and the repulsion caused by the Thomson Effect between baryons and photons, the results are acoustic waves propagating through the plasma, with the dark matter lumps being in the center of these waves.

The waves would propagate throughout the plasma as long as the baryon-photon interaction was strong enough i.e. up until recombination, point in which they froze in time leaving higher density regions. Higher density means higher gravitational intensity, which means higher galaxy proliferation in spherical distributions. These spherical distributions (which can be measured in the CMB) are what is known as the large scale structure of the universe.

These structures offer a lot of information about the size of the 'cosmic ruler' of the universe, allowing better and better accuracy in big scale cosmic measurements. The radii ($r_s \approx 150Mpc \approx 500$ million lightyears) of the spherical waves, the sound horizon, can be measured both in the CMB radiation, as we have already seen, and through the nearby galaxies. It has been verified that the *comoving* measurements [1] of r_s is constant throughout the universe.

1.4. Curvature, dark matter and the expansion of the universe

After Hubble discovered the expansion of the universe through Hubble's Law

$$v = H_0 d \tag{1.1}$$

With v the recession speed (the speed at which some point in space is receeding only considering the expansion of the universe), $H_0 = 100h\frac{km}{s}Mpc^{-1}$ Hubble's constant and d the distance of said point, a great deal of studies concerning the expansion of the universe started. The most relevant result of those for this report are Friedmann's equations.

$$H^2(t) := \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda c^2}{3} - K\frac{c^2}{a^2} \tag{1.2}$$

$$3\frac{\ddot{a}}{a} = \Lambda c^2 - 4\pi G\left(\rho + \frac{3p}{c^2}\right) \tag{1.3}$$

In these equations we see many new paramaters. $H(t)$ is a generalization of H_0, H_0 being the value of $H(t)$ at present time. $a(t)$ is the size factor of the universe, meaning

[1] The distance measured if the cosmological expansion did not exist

that if a certain distance measurement Δx was taken at time t_1, then that same measurement would be $\frac{a(t_2)}{a(t_1)}\Delta x$ at t_2. G is the universal gravitational constant, ρ is just the matter density of the universe (baryonic, dark matter, etc), Λ is the cosmological constant which contains information about Dark Energy. Finally we see K, which is the Gaussian Curvature of the universe. This is, asymptotical curvature.

If one managed to solve this differential equation, the result would a description of the history of the expansion of the universe. Moreover, it is also important to notice the relationship between the expansion of the universe and the distribution of matter in the universe.

El concepto de expansión del universo aparece cuando Erwin Hubble observa que las mediciones de la longitud de onda de radiación de las galaxias alrededor nuestra estaban todas desplazadas hacia el rojo. Es decir, estaban dilatadas. Esto indica que debido a la expansión del universo la longitud de onda de la radiación observada se habrá dilatado. Introducimos así la Ley de Hubble

k Que nos relaciona la velocidad de expansión de un punto separado una distancia d del observador, a través de la constante de Hubble $H_0 = 100h\frac{km}{s \cdot Mpc}$, siendo h un factor que permite parametrizar nuestro desconocimiento sobre H_0. H_0 representa realmente el valor actual de $H(t)$, así como cualquier observable cosmológico A_0 representa el valor actual de $A(t)$.

Introducimos así el concepto *redshift* como variable temporal.

$$z = \frac{\lambda_{\text{observado}} - \lambda_{\text{emitido}}}{\lambda_{\text{emitido}}} \tag{1.4}$$

La luz necesita tiempo para llegar a su destino, y durante ese tiempo el universo se habrá expandido cierta cantidad. Esa cantidad desplaza la radiación hacia el rojo dándonos una idea de cuánto tiempo ha estado la onda viajando, es decir cuál es la edad del objeto que estamos observando.

La expansión del universo viene parametrizada por un factor de escala $a(t)$, de tal forma que si en cierto momento medimos una distancia $a(t_0)\Delta x$, pasado un cierto tiempo Δt la nueva medida de esa misma distancia resultará en $a(t_0 + \Delta t)\Delta x$[2]

Es decir, que si consiguiésemos averiguar la expresión de $a(t)$, podríamos determinar la historia del universo. Alexander Friedmann desarrolló en 1922 las ecuaciones de Friedmann en las que define formalmente el ya mencionado parámetro de Hubble $H(t)$ Siendo G la constante universal de gravitación, ρ la densidad de materia del universo, Λ la constante cosmológica, K la curvatura Gaussiana del universo y p la presión del universo.

Se puede expresar la ecuación (1.2) de una forma más legible, definiendo los parámetros

$$\Omega_m = \frac{8\pi G\rho}{3H^2}, \Omega_\Lambda = \frac{\Lambda c^2}{3H^2}, \Omega_K = -K\frac{c^2}{H^2 a^2} \tag{1.6}$$

Conocidos como los parámetros de densidad, de vacío y de curvatura. Los dos primeros son los que contienen la información de la densidad de los fotones, neutrinos, bariones, materia oscura y energía oscura.

Reescribimos así la ecuación (1.2)

$$1 = \Omega_m + \Omega_\Lambda + \Omega_K \tag{1.7}$$

[2] Más precisamente, $a(t)$ aparece en la métrica de Friedman-Lemaître-Robertson-Walker (FLRW)

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right) \tag{1.5}$$

Que es la ecuación que cumplirá cualquier universo que estudiemos, entendiendo por universo o cosmología los diferentes valores que se le den a los parámetros Ω

Con estos conceptos podemos relacionar el *redshift* con el factor $a(t)$

$$1+z = 1+\frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{a(t_o)}{a(t_e)} \tag{1.8}$$

La ecuación (1.8) nos permite relacionar el factor de escala actual con el que había en el universo en el momento de emisión de la radiación observada, en función del *redshift*que observemos.

Otra relación importante será también la que nos permite calcular el parámetro de Hubble en función de la cosmología que escojamos

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda} \tag{1.9}$$

A través de la constante de Hubble calculamos también la distancia de Hubble

$$D_H = \frac{c}{H(z)} \tag{1.10}$$

Que actualmente toma un valor de $D_H = 3000h^{-1}$Mpc. La distancia de Hubble se define como la distancia a partir de la cual la velocidad de expansión del universo relativa al observador es mayor a la velocidad de la luz[3]

Aquí explico los parámetros que afectan a la expansión del universo y por tanto al redshift y por tanto a las medidas que tomamos.

1.5. Oscilaciones Acústicas de Bariones.

Las concentraciones de materia implicaban unas intensas interacciones que al equilibrarse con la presión de radiación, daban lugar a la propagación de ondas acústica de manera isótropa por el mencionado plasma, que se propagabn a una velocidad usualmente aproximada según $v = \frac{c}{\sqrt{3}}$.

1.6. El Fondo Cósmico de Microondas.

1.7. La estructura a gran escala del universo.

1.8. La escala BAO como regla estándar.

[3]Si sustituimos $v = c$ en (1.1), sustituimos $v = c$ y despejamos la D correspondiente queda exactamente la expresión de D_H

CHAPTER 2

Resultados

2.1. Cálculo de observables

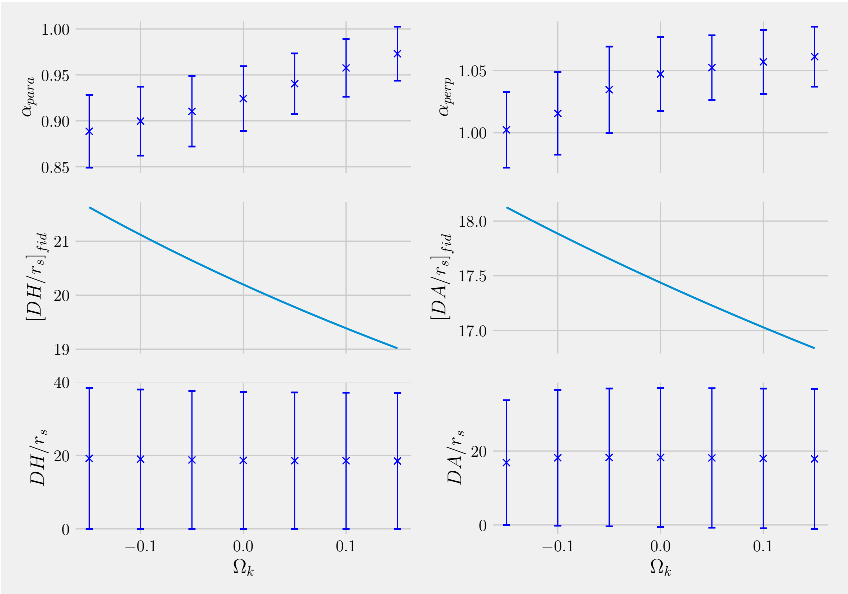

Figura 2.1: Cálculo de los observables cosmológicos para diferentes cosmologías

Conclusiones

En este trabajo ...

Conclusions

In this work ...

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Anexo: Ejemplo para introducir código Matlab

```
%% 3-D Plots
% Three-dimensional plots typically display a surface
% defined by a function in two variables, z = f(x,y) .
%%
% To evaluate z, first create a set of (x,y) points
% over the domain of the function using meshgrid.
    [X,Y] = meshgrid(-2:.2:2);
    Z = X .* exp(-X.^2 - Y.^2);
%%
% Then, create a surface plot.
    surf(X,Y,Z)
%%
% Both the surf function and its companion mesh display
% surfaces in three dimensions. surf displays both the
% connecting lines and the faces of the surface in color.
% Mesh produces wireframe surfaces that color only the
%lines connecting the defining points.
```

Anexo: Ejemplo para introducir código ISE

```
library IEEE;
            use IEEE.STD_LOGIC_1164.ALL;
            use IEEE.STD_LOGIC_ARITH.ALL;
            use IEEE.STD_LOGIC_UNSIGNED.ALL;
-- Uncomment the following library declaration if
-- instantiating  any Xilinx primitive in this code.
-- library UNISIM;
-- use UNISIM.VComponents.all;

entity counter is
    Port ( CLOCK : in  STD_LOGIC;
    DIRECTION :    in  STD_LOGIC;
    COUNT_OUT :    out STD_LOGIC_VECTOR (3 downto 0));
end counter;

architecture Behavioral of counter is
signal count_int : std_logic_vector(3 downto 0) := "0000";
begin
process (CLOCK)
begin
    if CLOCK='1' and CLOCK'event then
        if DIRECTION='1' then
            count_int <= count_int + 1;
        else
            count_int <= count_int - 1;
        end if;
    end if;
end process;
COUNT_OUT <= count_int;
end Behavioral;
```