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# COSMOLOGY AND STRUCTURE FORMATION WITH THE GTM AND GTC

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RESUMEN

¿Cómo se forma estructura en el universo? La nueva generación de telescopios, tales como el Gran Telescopio Milimétrico (GTM) y el Gran Telescopio Canarias (GTC), pueden jugar un papel importante para ayudarnos a entender este problema. Estamos apoyando un nuevo grupo de investigación en el INAOE y en Barcelona centrado en la cosmología milimétrica y la formación de estructuras. Presentamos un breve resumen del tema y su posible relación con las dos nuevas infraestructuras en España y México.

ABSTRACT

How does structure form in the Universe? The new generation of telescopes, such as the Gran Telescopio Milimétrico (GTM) and Gran Telescopio de Canarias (GTC), can play a major role in understanding this problem. Ongoing efforts at INAOE and Barcelona are focused on developing a new research group centered around millimeter cosmology and structure formation. We present a brief summary of the subject and its possible connection with the two new facilities in Spain and Mexico.

*Key Words:* **COSMOLOGY — LARGE SCALE STRUCTURE**

## 1. INTRODUCTION

Structure formation is an initial conditions problem: initial inhomogeneities grow through gravity to produce collapsed objects, such as stars and galaxies. There are some important links between early structure formation, the matter–energy content in the Universe, and the problem of understanding galaxy formation. Let us briefly review some of these ideas.

Comoving coordinates $\boldsymbol{x}$ relate to physical coordinates by $\boldsymbol{r}_p = a(t)\,\boldsymbol{x}$, where $a(t) = (1+z)^{-1}$ is the cosmic scale factor, and $z$ the corresponding redshift ($a_0 \equiv 1$). Thus all geometrical aspects of the universal line element are determined up to the function $a(t)$ and the arbitrary constant $k$, which defines the usual open, Einstein–de Sitter and closed universes. The function $a(t)$ can be found for each matter–energy content, $\rho$, by solving the corresponding equations of motion:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho}{3} + \frac{k}{a^2} + \frac{\Lambda}{3}, \qquad (1)$$

where $\Lambda$ is the cosmological constant. We can divide $\rho$ into matter (non-relativistic) and radiation (relativistic) energy density: $\rho = \rho_m + \rho_\gamma$. In a matter-dominated (MD) regime, $\rho \simeq \rho_m \simeq \rho_m(0)\ a^{-3}$, because the volume increases with the expansion. In the radiation-dominated (RD) regime, $\rho \simeq \rho_\gamma \simeq \rho_\gamma(0)\ a^{-4}$, because of the additional loss of energy of photons (or relativistic matter) as the Universe expands. Equation 1 for the Hubble rate, $H$, can be rewritten using the notation $\Omega \equiv 8\pi G\rho(0)/(3H_0^2)$, which is the ratio of the current density, $\rho(0)$, to the critical density, $\rho_c \equiv (3\ H_0^2)/(8\pi G) \simeq 2.78 \times 10^{11}\ M_\odot\ h^2/\mathrm{Mpc}^3$, where $h$ is defined as $H_0 \equiv 100\ h$ km s$^{-1}$ Mpc$^{-1}$. We also define $\Omega_k = k/H_0^2$ as the global curvature, and $\Omega_\Lambda = \Lambda/(3H_0^2)$, so that

$$H^2 = H_0^2\ \left[\ \Omega_m a^{-3} + \Omega_\gamma a^{-4} + \Omega_k a^{-2} + \Omega_\Lambda\ \right], \quad (2)$$

with $\Omega_m + \Omega_\gamma + \Omega_k + \Omega_\Lambda = 1$. In other words, the total matter–energy content, $\Omega_T = \Omega_m + \Omega_\gamma + \Omega_\Lambda$, produces a universe with a metric curvature: $\Omega_k = 1 - \Omega_T$. We can further write the matter density $\Omega_m = \Omega_B + \Omega_{\mathrm{DM}}$. $\Omega_B$ derives from the baryonic component and is measured to be $\Omega_B \simeq 0.02h^{-2}$ using primordial nucleosynthesis (Fiorentini et al. 1998). $\Omega_{\mathrm{DM}}$ is the non-baryonic (dark) matter contribution. The current values of the *cosmological parameters* $\Omega_m, \Omega_B, \Omega_\gamma, \Omega_\Lambda$, and $H_0$ determine the evolution of $a(t)$ in the above equation, i.e., the metric and dynamics of the Universe.

It is clear by inspecting equation 2 that at early times ($a \rightarrow 0$) the expansion is dominated by radia-

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tion (RD). In this case, it is easy to find from equation 2 that the solution to the expansion factor is $a_{\rm RD} \sim t^{1/2}$. Later, the Universe is matter-dominated (MD) and we have $a_{\rm MD} \sim t^{2/3}$.

## 2. THE STRUCTURE FORMATION PUZZLE

At a given cosmic time, $t$, from the initial singularity, light has travel a distance $d_h = ct$, its *causal horizon*. This is typically proportional to the Hubble radius, defined as $c/H(t)$. For MD, $a_{\rm MD} \sim t^{2/3}$, we have $d_h \sim a^{3/2}$, while for the RD regime, $a_{\rm RD} \sim t^{1/2}$, we have $d_h \sim a^2$. Note that this means that the horizon grows faster with $a$ than any physical scale, $\lambda$, which grows as the expansion factor $\lambda \sim a$. If we now look back in time, this means that any given physical scale was out of causal contact at very early times and enter the horizon at some time $a_{\rm enter}$ given by $d_h = \lambda$. The existence of horizons gives rise to two problems in the cosmological model:

1. Photons in the cosmic microwave background (CMB, see below) that reach us from different directions (separated by more than one degree in the sky) have never been in causal contact (i.e., the physical distance $\lambda$ that separated them on emission was larger than the horizon $d_h$ at that time ($z = 1100$). If so, how is the CMB temperature from different directions in the sky the same to within one part in $10^5$?

2. Physical scales smaller than $\simeq$ 100 Mpc entered into causal contact when the Universe was radiation-dominated. The coupling of matter and the thermal radiation bath will erase (smooth) any fluctuations present in the initial conditions. What, then, is the origin of structure on scales smaller than $\simeq$ 100 Mpc?

Inflation solves the first of these problems by postulating that at some early times the Hubble rate is dominated by a large vacuum energy (i.e., by $\Omega_\Lambda$) of some scalar field $\phi$ (the inflaton) with a potential $V(\phi)$ as sketched in Figure 1. The field $\phi$ starts at a point of high vacuum energy, $E = V(\phi)$, and slowly roles towards its minimum. While the energy is dominated by the vacuum, the solution to Hubble's equation 2 is: $a \simeq e^{tH}$, i.e., the Universe inflates exponentially. After some time of slow role inflation, the inflaton energy roles down to its minimum. This reduces the potential energy, which is converted into kinetic energy and later into radiation (re-heating) through damped oscillations around the potential's minimum (see Figure 1). Thus, after some time of

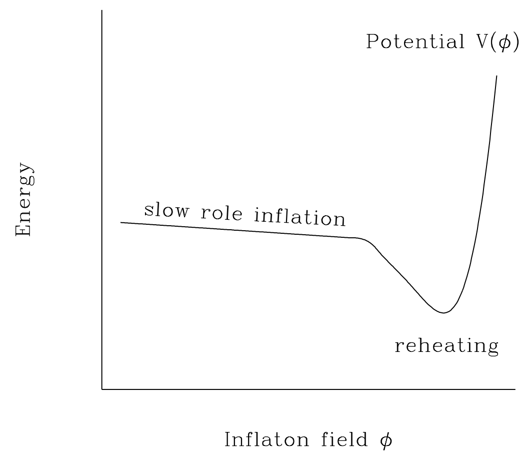


Fig. 1. Sketch showing the inflaton potential, $V(\phi)$.

inflation, equation 2 is dominated by the radiation (RD) and later by matter (MD). This solves the first problem because the horizon during inflation is $d_H \simeq \ln a$, which means that physical distances were in fact in causal contact earlier in the past and went beyond the horizon during inflation, and re-entered into causal contact after inflation ended. This also implies that the curvature $k$ is reduced exponentially, so that one would expected a flat universe, $\Omega_T = 1$, after inflation.

The second problem is solved by postulating the existence of cold dark matter (CDM), which does not couple to radiation (i.e., it is non-baryonic). The possible existence of this non-baryonic CDM seems to agree with the observational fact that $\Omega_m > \Omega_B$ and also with other observational indications, such as rotation curves in galaxies.

### 2.1. *Linear growth and the Jeans instability*

In the fluid approximation, deviations from the mean background, $\overline{\rho}$, are characterized by fluctuations in the density (and velocity) field: $\delta(\boldsymbol{x},\tau) \equiv \rho(\boldsymbol{x},\tau)/\overline{\rho} - 1$. In the linear regime of matter domination, the spatial and temporal part factorize: $\delta(\boldsymbol{x},\tau) = \delta_0(\boldsymbol{x})\, D(\tau)$, where $D$ is usually referred to as the *linear growth factor*. Thus initial fluctuations, no matter of what size, are amplified by the same factor, and the statistical properties of the initial field are just linearly scaled. For example, the power spectrum of fluctuations is

$$P_l(k) \equiv \langle \delta_k^2(k) \rangle = D^2\ P_0(k), \tag{3}$$

where $P_0(k)$ is the initial primordial spectrum.

In general, there is also a pressure term in the cosmic fluid (because of radiation and hot gas) that contributes to the restoring force in the linear harmonic equation. The expressions in this case are simplied if we consider a Fourier decomposition of $\delta$ in Fourier modes $\delta_k$. The linear equation is

$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\,\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\;\mathcal{H}^2\,\Omega_m - k^2\;v_s^2\right)\;\delta_k = 0, \quad (4)$$

where $v_s$ is the fluid sound speed, $v_s^2 = (\partial p/\partial \rho)$ and $k = 2\pi/\lambda$ is the wavenumber corresponding to the mode $\delta_k$. The solution to the above harmonic oscillator depends on which term dominates the restoring force. If $\frac{3}{2}\,\mathcal{H}^2\,\Omega_m > k^2\,v_s^2$, the fluctuations will grow, otherwise they will follow damped harmonic oscillations. The damping rate is giving by $\mathcal{H}$. The critical scale—the Jeans scale, $k_J = 2\pi/\lambda_J$—is given by: $k_J^2 = \frac{3}{2}\,(\mathcal{H}^2\Omega_m)/(v_s^2)$. Fluctuations on scales smaller than $\lambda_J$ are damped by the pressure, while larger fluctuations grow because of gravity. If we measure the Jeans scale we can estimate the cosmological parameters. As mentioned above, for most scales of astronomical interest, fluctuations enter the horizon when the universe is RD. If matter couples to radiation, as baryons do, they will feel the radiation pressure and fluctuations will be damped. CDM does not couple to radiation, which means that it only feels the pressure through the background evolution of the Hubble equation.

### 2.2. *The spectrum of fluctuations*

The Jeans instability transforms the linear spectrum of fluctuations in equation 3 as

$$P(k) = P_l(k)\;T^2(k) = D^2\;P_0(k)\;T^2(k), \quad (5)$$

where $T(k)$ is called the *linear transfer function*, and encodes the transition of fluctuations through the MD phase of the Universe as explained above. This transfer function has a characteristic scale $k_{\rm break} \simeq \Omega_M h^2$ which corresponds to the scale of the horizon on the transition between MD and RD. For large scales ($k \ll k_{\rm break}$) we will have $T(k) \simeq 1$, as fluctuations enter the horizon in the MD phase, while for $k \gg k_{\rm break}$ we will have $T(k) \simeq 0$, as fluctuations are exponentially suppressed. During inflation, quantum fluctuations of the $\phi$ field are inflated into large classical fluctuations. These quantum fluctuations have a scale-invariant spectrum of energy fluctuations. This translates into $P_0(k) \sim k$ for the primordial spectrum of density fluctuations.

As the universe cools down to $T \simeq 3000$ K, photons decouple from baryons because they are no longer energetic enough to prevent the formation of neutral atoms. This occurs at a time $a_{\rm decoupling}$ corresponding to $z \simeq 10^3$, which is called the surface of last scattering. Photons can then travel freely in space and are measured as the cosmic microwave background (CMB) radiation. Density fluctuations present at the surface of last scattering translate into temperature fluctuations in the CMB. Using similar calculations one can also estimate the spectrum of angular temperature fluctuations in the CMB, $c_l$. This spectrum also depends on the cosmological parameters both because of curvature and projection effects and also because of the Jeans scale. It has characteristic acoustic peaks that reflect the damped oscillations present at the moment of decoupling.

Thus, if we can estimated $P(k)$ or $c_l$ from observations, we can use the above model to estimate the cosmological parameters. It is commonly assumed by astronomers that inflation predicts a scale-invariant Harrison–Zel'dovich (H–Z) primordial spectrum of scalar density Gaussian perturbations, $P_0(k) \propto k^n$ with $n = 1$, as the initial condition for structure formation. This is an essential ingredient when fitting cosmological parameters, such as the baryon density, $\Omega_{\rm B}$, to observations of large scale structure or CMB fluctuations (de Bernadis et al. 2000; Hanany et al. 2000). Relaxing this assumption, produces quite different constraints (Adams et al. 1997; Barriga et al. 2001).

## 3. MM COSMOLOGY AND THE LMT

After some time, linear fluctuations evolve into the weakly non-linear regime and later collapse to form the first generation of stars and galaxies. Although we seem to understand the rudiments of non-linear gravitational collapse (Bernardeau et al. 2001), we know little of how and when galaxies form. The above cosmological framework seems to favor a hierarchical model where the smallest objects form first and later build larger objects. Clusters of galaxies are the largest bound structures in the Universe and their evolution (e.g., the Press–Schechter formalism) can be used to put severe constraints on cosmological parameters. This evolution is still subject to large observational uncertainties. There is observational evidence for recent ($z < 1$) star formation evolution in the blue compact galaxy population, but there is no evidence of much evolution in large elliptical galaxies. This seems to be in apparent contradiction with the above hierarchical picture. When did the large elliptical galaxies form?

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The primary optical and UV radiation emitted by the first generations of young massive stars in galaxies is absorbed by dust and re-radiated at FIR wavelengths. In distant galaxies this rest-frame FIR emission is redshifted to longer wavelengths because of the expansion of the Universe. The formation of galaxies is therefore expected to be a spectacular luminous event at sub-mm and mm wavelengths (e.g., Hughes & Gaztañaga 2000 and references therein). Are the bright sources observed with the SCUBA (JCMT) at 0.85 mm the progenitors of present-day massive elliptical galaxies? As these SCUBA sources lack reliable optical/IR identification, we have no direct way to measure their redshifts. There are two ways in which we can improve this situation. One is through photometric redshifts (Hughes et al. 2001); the other is by searching for two adjacent CO lines with ultra broad-band mm receivers (e.g., $nu_R = 35$ GHz).

The Large Millimeter Telescope (LMT[1]), a 50 m telescope that will be operated by INAOE/Umass from Mexico, will be able to search for these CO lines. This can be combined with the fast imaging capabilities to reproduce both the luminosity evolution and clustering properties of the early star forming regions. Large blank field maps will trace the underlying density fluctuations at high redshifts. The spectrum and statistics of such maps (Gaztañaga & Hughes 2001) can be used to fill in the gaps in the current structure formation puzzle.

As the CMB peaks at millimeter wavelengths, the LMT will be able map CMB background fluctuations on scales that are unavailable to current and future CMB experiments.

### 3.1. *Cluster evolution: the SZ effect*

Trapped in the potential wells of clusters of galaxies lies a hot, tenuous, and fully ionized gas ($T_e = 10^8$ K, $n_e = 10^{-3}$ cm$^{-3}$) that is the major component of the intra-cluster medium (ICM) and the clusters' baryonic content. Sunyaev and Zel'dovich showed that the CMB photons and the electrons in the ICM can interact through the inverse Compton effect resulting in a scattering process. This process preserves the number of CMB photons, but gives a net energy gain to the CMB photons in the cluster's line of sight. Thus the CMB is spectrally distorted. This process, the Sunyaev–Zel'dovich effect (SZE), offers a robust method for the detection of galaxy clusters which is, almost, independent of redshift. With the right instrumentation, the LMT would be ideal to systematically detect this cluster population (Lopez-Cruz & Gaztañaga 2000).

[1]See http://www.lmtgtm.org.

## 4. THE ROLE OF THE GTC

What could be the role of the Gran Telescopio Canarias (GTC) in connection to the LMT and the above cosmological puzzles? A possible role could be to find optical identifications of the LMT/SCUBA/BLAST surveys propose in (Hughes et al. 2001), but the spectral energy distribution (SED) of these sources indicates very high optical extinction. It remains to be seen whether the GTC will be able to detect such objects if they are at $z > 3$.

One could also imagine using the FIR capabilities of CanariCam + GTC to get closer to the mm band and help in the photometric redshift identification of such sources. In order for this to be possible we need a better modeling of the SED for star forming galaxies at tens of microns.

OSIRIS + GTC seems a perfect instrument to conduct spectroscopic follow-up of SZE cluster positions provided by LMT. This will reveal the redshift evolution of a well-defined SZE cluster population, which in turn will provide strong constraints on the cosmological models, e.g., using Press–Schechter formalism to determine $\Omega_\Lambda$ (Holder et al. 1999).

The unique imaging and spectroscopic capabilities of EMIR + GTC could be used to produce blank field maps with both redshifts and angular positions of the high redshift galaxy population. This, in combination with other data, can be used to understand the star formation history of such populations. It will also provide the clustering information that relates them to the initial conditions.

It seems to us that the most efficient approach to exploiting the uniqueness of the GTC instrumentation would be to define key projects to conduct large blank field multiwavelength surveys. As in the Sloan Digital Sky Survey (SDSS, www.sdss.org), these surveys can be use to explore a wide range of areas, from solar to galactic and extra-galactic physics. We believe that such an approach would be ideal for combining the LMT and the GTC and advance our understanding of structure formation.

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