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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. To support this effort, a new research group with interests in millimeter cosmology and structure formation is being developed at INAOE and Barcelona. We present a brief summary of the subject and and the contribution that can be made with the two new facilities in Spain and Mexico.

Key Words: **COSMOLOGY — LARGSE 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.

Recall that 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, ρ, 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 Λ is the cosmological constant. We can divide ρ 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

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

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 $\Omega_m = \Omega_B + \Omega_{\rm DM}$. Ω_B derives from the baryonic component and is measured to be $\Omega_B \simeq 0.02h^{-2}$ using primordial nucleosynthesis (Fiorentini et al. 1998). $\Omega_{\rm DM}$ 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 ($a \to 0$) the expansion is dominated by radiation. 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 and we have $a_{\rm MD} \sim t^{2/3}$.

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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, λ, 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 enters the horizon at some time $a_{\rm enter}$ given by $d_h = \lambda$. The existence of horizons introduces 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 λ that separated them on emission was larger than the horizon d_h at that time ($z = 1100$). If this is the case, why 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 Ω_Λ) of some scalar field ϕ (the inflaton) with a potential $V(\phi)$ as sketched in Figure 1. The field ϕ 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 period of inflation, equation 2 is dominated by the radiation and later by matter. 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

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

the curvature k is reduced exponentially, so that one would naturally expect 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 the flat 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 called 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 δ in Fourier modes δ_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 δ_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 given 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 λ_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

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

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 at 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 ϕ 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). Relaxing this assumption, produces quite different constraints (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?

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 rest-frame FIR wavelengths. The formation of galaxies is therefore expected to be a spectacular luminous event at sub-mm and mm wavelengths. Are the bright submm sources observed with the SCUBA (on the

JCMT) at 0.85 mm the progenitors of present-day massive elliptical galaxies? As these SCUBA sources often lack reliable optical/IR identifications, we have no direct way to measure their redshifts. There are two ways in which we can improve this situation. One method uses photometric redshifts (Hughes et al. 2001) derived from rest-frame FIR to radio colors. Alternatively the molecular CO emission lines can be detected directly using ultra broad-band mm receivers (e.g., $\Delta\nu = 35$ GHz).

The Gran Telescopio Milimétrico (GTM, http://www.lmtgtm.org), a 50 m telescope that will be operated by INAOE/UMass from Tonantzintla, Mexico, will conduct searches for these CO lines. Due to the sensitivity and fast mapping-speed of the GTM, the measured mm-wavelength source-counts and clustering properties of this high-z, luminous starburst population can be accurately measured. Together with the redshift distribution derived from the detected CO-lines, the luminosity evolution and star formation history of early starburst galaxies can be constrained.

As the CMB peaks at millimeter wavelengths, the GTM will also be able map CMB background fluctuations on smaller scales than 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, $n_e = 10^{-3}\,\mathrm{cm}^{-3}$) which is the major component of the intra-cluster medium (ICM) and the clusters' baryonic content. Sunyaev and Zeldovich 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. Again the GTM will systematically detect this cluster population (Lopez-Cruz & Gaztañaga 2000) through blank-field surveys.

4. THE ROLE OF THE GTC

What could be the role of the Gran Telescopio Canarias (GTC) in connexion to the GTM and the above cosmological puzzles? One possible programme is to exploit the unique imaging and spectroscopic capabilities of EMIR on the GTC, and find the heavily reddened ($I-K > 6$) and faint IR counterparts ($K > 21$) of the mm sources detected in the GTM surveys, and thereafter measure their spectroscopic redshifts at IR wavelengths. The combination of the positional and redshift information of this mm population of starburst galaxies will determine their clustering properties, which are sensitive to the initial conditions of their formation.

The high-resolution and sensitive mid-IR imaging of submm galaxies, using CanariCam on the GTC, will help discriminate between dust heated by an active galactic nucleus (AGN), or a powerful starburst, as the source of the mid-IR luminosity. These data will help determine the AGN fraction in the submm population.

Using OSIRIS on the GTC, one can make spectroscopic follow-up observations of the galaxies associated with high-z clusters, detected initially through the SZE with the GTM. The redshift evolution of a well-defined SZE cluster population will provide strong constraints on the cosmological models (e.g., using Press–Schechter formalism) and the determination of Ω_Λ (Holder et al. 1999).

We can advance our understanding of structure formation in the high-z Universe by exploiting the uniqueness of the GTC and the GTM. An efficient method would be to define common key projects (such as wide-area blank-field extragalactic surveys) that take advantage of their combined optical, IR, mid-IR and mm-wavelength imaging and spectroscopic capabilities.

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