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GALAXY FORMATION AND THE GTC

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RESUMEN

Una revisión de las cuentas de galaxias débiles y de los mapas de corrimientos al rojo indica la oportunidad científica de responder una pregunta básica acerca de la formación galáctica usando el GTC: ¿Cómo y cuando se agrega la masa? Entendemos que la clave para responder a esta pregunta es el análisis del "límite débil" de la función de luminosidad de galaxias hasta al menos $z = 2$. Esto puede alcanzarse con un trabajo coordinado que comienza con cuentas profundas en óptico e infrarrojo cercano, seguido de espectroscopía multiobjeto en NIR, y completado con espectroscopía de campo integral usando óptica adaptativa.

ABSTRACT

A review of faint galaxy counts and redshift surveys points to a scientific opportunity for the Gran Telecopio Canarias (GTC) to answer a basic question about galaxy formation: How and when did mass assemble? We argue that the key to answering this question is by focusing on the "faint-end" of the galaxy luminosity function out to at least $z = 2$. This can be exploited with a concerted effort starting with deep counts in the optical and near infrared, followed with near-infrared multiobject spectroscopy, and completed with integral field spectroscopy employing adaptive optics.

Key Words: **GALAXIES: EVOLUTION — GALAXIES: FORMATION**

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1. INTRODUCTION

An important yet unanswered question about galaxy formation and evolution is: How and when did mass assemble? Deep, multiband imaging surveys with the *Hubble Space Telescope* (*HST*) and large, ground-based telescopes are now used routinely to detect galaxies at distant epochs when galaxies clearly are very young. But such data are limited to measuring distributions of light—not mass.

Structure formation within the currently hegemonic cold, dark matter scenarios (CDM) gives several crisp predictions of how galaxy formation should proceed. Hierarchical merging, for example, implies down-sizing of star formation sites with cosmic time, i.e., the comoving star formation rate should be dominated in early times by massive systems, and at late times in low mass systems. Do we see this?

It is now relatively straightforward to make a first-order estimate of comoving star formation rates, but the same cannot be true of comoving mass functions. We still ponder if we have the right extinction corrections and whether we can properly stitch together star formation indices across redshift and wavelength. These are important concerns. But the uncertainties plaguing mass estimates based on photometry alone are much more significant at high redshift. For composite stellar populations with young (or strongly bursting) components, mass-to-light ratios are very difficult to assess from photometry. In this regime, even color is not always a sufficient second parameter to transform luminosity into mass. The neutral and molecular gas content, dark-matter content, and distributions of these quantities is also unknown in systems at high redshift, but it is likely different than in today's galaxies.

To assess galaxy formation, the challenge is to connect galaxy populations across time. Since formation and transformation (evolution) are intertwined, such an approach may be ill-posed, and instead it may make more sense to assess the content of representative comoving volumes. However, since surveys are not volume-limited, we must either tracking populations or understand what populations are above and below our detection limits as a function of redshift. One way or the other, we are stuck with the limitation that we observe galaxy light, and light does not always trace mass well. For example, do we know that "faint" always means low mass and "bright" means high mass at all redshifts? This would be tantamount to understanding the evolution of Tully–Fisher and fundamental plane-like relations spanning luminosities from giants to dwarfs.

Ultimately, we want to understand how the mass function evolves. To measure galaxy mass, dynam-

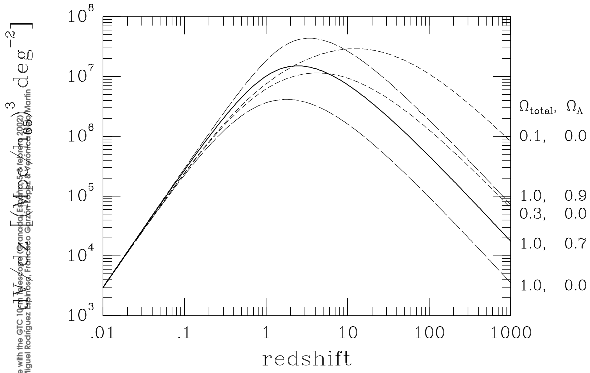

Fig. 1. The cosmological differential volume element for a range of observationally plausible density parameters, Ω. Volumes pinch off at $2 < z < 15$ for all $\Omega_{\rm total} \leq 1$, while $\Omega_\Lambda = 0$ cosmologies pinch off later. For the currently favored $\Omega_{\rm total} = 1.0$, $\Omega_\Lambda = 0.7$ cosmology, the differential volume-element peaks at $z = 2.5$.

ical estimates are more reliable than photometric ones, but the former require kinematic measurements from spectroscopy that are expensive relative to photometry. What, then, is the best observational strategy? One approach is to determine the evolution of the luminosity function and sample the characteristic mass at bright and faint ends. Taking the generic predictions of CDM as a foil, however, one might estimate the characteristic mass, as a function of epoch, of those galaxies which appear to dominate the comoving star formation rate. Conveniently, this has the best chance of being observationally tractable because the sources will be relatively luminous and have strong line emission.

In the balance of this paper I will argue that the GTC is well poised to study the "faint-end" of the galaxy *luminosity* function to $z \sim 2$ by coupling deep optical and near-infrared counts with EMIR's multiobject spectroscopic capability. A future challenge will be to transform this into a measurement of the evolution of the mass function. We argue this will require multiobject integral field spectroscopy with adaptive optics.

2. GALAXY COUNTS

Galaxy counts simply represent sums of luminosity functions modulated by shifts in apparent magnitude (due to the cosmological luminosity–distance, d_L, K-corrections, and evolutionary corrections) and in apparent number (due to changes in the volume element, dV/dz with redshift). Despite this conceptual simplicity, the number of contributing parameters makes the interpretation of galaxy counts (slope and normalization) difficult without further information, such as color and redshift.

Nonetheless, we are often lured into thinking that the faint counts are dominated by galaxies at high redshift, i.e., that "faint" means "far away." Because of the Malmquist bias in a cosmological setting for galaxy luminosity functions, the above conclusion is false statistically—at least for wavelengths dominated by starlight.

For example, it has been claimed that the galaxy counts ought to roll over or change slope at sufficiently faint magnitudes because of either the pinching-off of the cosmological volume element at high redshift (see Figure 1) or the snuffing out of flux as the Lyman break shifts into the observed passband. Certainly, it is true that the volume element begins to decrease beyond $1.5 < z < 3$ for any reasonable cosmology. However, for exactly this reason, the counts are never dominated by galaxies at higher redshifts: Galaxies near the redshift where the differential volume peaks will provide the dominant contribution to the counts for magnitudes fainter than $L*$ at the volume peak redshift, provided the faint end of the luminosity function is steeper than the trend of dV/dz with redshift.

Hence, the volume argument correctly implies that i) there is no roll-over in the counts due to volume pinch-off or Lyman break (for bands redward and including U) and ii) there should be a roll-over *only* if/when the faint end of the galaxy luminosity function rolls over in redshift range $1.5 < z < 3$. In other words, the faint counts are dominated by the faint end of the galaxy luminosity function at $1.5 < z < 3$. This occurs at $B > 24$ or $K > 22$ as illustrated in Figures 2 and 3.

In these figures, adapted from Crawford et al. (2002), we have have used the luminosity functions measured from spectroscopic surveys at $z \sim 0$, $z \leq 1$, and $z \sim 3$ (Gardner et al. 1999 for the near infrared at $z \sim 0$; Blanton et al. 2001, Lilly et al. 1995, Cohen 2002, Shapley al. 2002 in the optical), and interpolated between surveys to estimate the luminosity function $\phi(M, z)$. We have split up the luminosity function by type (blue and red) as defined spectroscopically and assumed that between $z = 1$ and $z = 3$ the red luminosity function is gradually subsumed into the blue luminosity function as defined at $z = 3$ (i.e., there are no old galaxies at high redshift). In each of several representative redshift bins, we have transformed $\phi(M)$ to $\phi(m)$ using appropriate K-corrections and distance modulus, and multiplied by the differential volume element. In Figures 2 and 3, these are compared to the counts in the B and

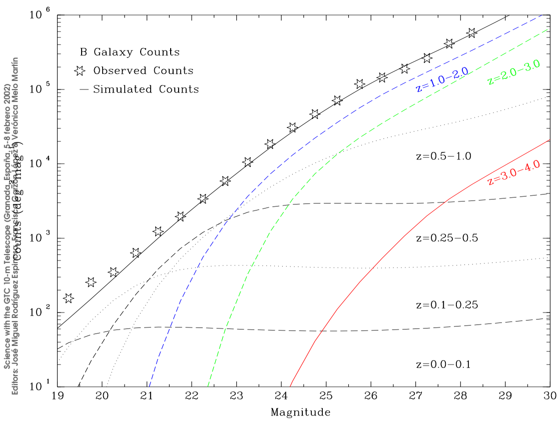

Fig. 2. B band galaxy counts and model based on observed luminosity function from $0 < z < 3$. Starred symbols represent observed counts as averaged over suitable surveys from the literature. The curves represent the contribution to the counts from bins in redshift (labeled), as determined from our empirical model based on observed luminosity functions from $0 < z < 3$. The top curve is the sum of all of these curves; it matches the observed counts well, as it should do if the observed luminosity functions are correct. Note that the model predicts the $1 < z < 2$ bin dominates the counts for all magnitudes fainter than $B = 23$, with the $2 < z < 3$ bin being the second largest contributor (20–30%) fainter than $B = 25.25$.

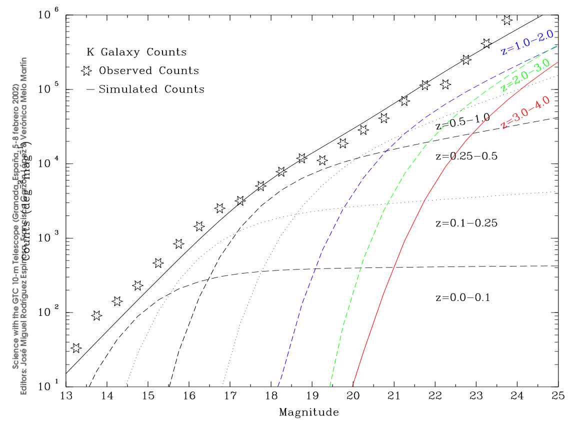

Fig. 3. K band galaxy counts and model, with model, symbols, and lines defined as for the B band counts. While the the $1 < z < 2$ bin dominates starting at $K = 21$, there is an equal contribution from the $2 < z < 3$ bin faintwards of $K = 23$—the present limit of count surveys.

the K bands. The sum of these bins matches the total counts—a consistency check between counts and luminosity functions derived from deep redshift surveys.

The above result means that in principle we can use the faint counts to study the faint end of the luminosity function at $1.5 < z < 3$. If we identify the slope of the galaxy counts as being dominated by the luminosity function in the regime where dV/dz peaks, it is straightforward to show:

$$\frac{d \log A(m)}{dm} = -0.4(\alpha + 1),$$

where α is the slope of the luminosity function $\phi(L)$ for $L \ll L*$. A review of the subset of the literature on galaxy counts—for which reliable photometry and completeness corrections have been made—yields faint-end count slopes of $\sim 0.31 \pm 0.04$ at a variety of wavelengths. This translates into $\alpha = -1.8 \pm 0.1$ at $1.5 < z < 3$.

There are some critical details that need to be worked out to make our analysis a precision measurement of α; these are are particularly well-suited to study with EMIR.

- Determine the bright end of the luminosity function in the "optical desert", i.e., between $1 < z < 2.5$, with near-infrared multiobject spectroscopy to constrain evolution at these epochs. Shapley et al.'s (2002) results imply there has been 1.5 mag of luminosity evolution at the bright end between $0 < z < 3$. What is the rate between $1.5 < z < 3$?

- Establish near-infrared luminosity functions at lower redshift in comparable detail to that in optical studies, i.e., to at least 1% of $L*$, and as a function of spectral type.

- Use these results to calculate more accurately the redshift wavelength dependence where the faint-end luminosity function dominates faint counts—owing to K- and E-corrections. This provides a means to use multiband counts to measure $\alpha(z)$ (cf. Figures 2 and 3).

At this time we can conclude that galaxy counts are well-described by extrapolating luminosity functions at the bright end, and that the faint end of the luminosity function has become very steep by $z = 1 - 2$. This appears to be qualitatively consistent with CDM scenarios. But what systems and what physical processes are driving the evolution of the luminosity function? For example, Guzmán et al. (1997) have suggested that luminous compact blue galaxies (LCBGs) are a significant contributor to the increase in the comoving star formation rate at intermediate redshift. Are they connected to the steepening of the luminosity function? If so, what triggers their star formation, and what have they become by today—spheroidals (e.g., Guzmán et al. 1998), bulges (e.g., Hammer et al. 2001), both, or something else? The next step in our understanding is to measure the internal kinematics and masses of these systems.

3. MEASURING DYNAMICAL MASS

As we argued in the introduction, mass needs to be measured from kinematics and not just photometry—at least for actively star forming galaxies (total mass always requires kinematic measurement). In the crudest form, a spectroscopic line width and characteristic size provides a dynamical mass estimate. For disk systems, however, one strongly prefers a rotation curve to a line width. Spatially resolved kinematics are required because all observational systematics due to poor signal-to-noise (S/N) or spatial resolution conspire to lower observed velocities (see, for example, the study of Pisano et al. 2001 on nearby LCBGs). Without minimizing these observational systematics one erroneously infers systematically smaller masses with increasing redshift—qualitatively as expected from CDM theory. In general, one would like to understand if an observed line width is dominated by coherent, ordered motions, such as rotation; random motions, but in a relaxed velocity field; or disturbed, non-equilibrium flows.

What spatial resolution is needed for kinematic measurements? Higher is obviously better, but one must avoid photon starvation! Without knowing a priori if the light distribution matches the dynamical scale, ideally one should aim at first to resolve the optical image. Since distant galaxies are characteristically small (half-light radii of a few tenths of an arcsecond), the required angular resolution for faint sources is terrifyingly high—even for 10 m class telescopes. However, Koo's (1999) simulations illustrate that bright knots of line emission (i.e., H II regions) may provide regions of high contrast and high surface brightness which make such high resolution measurements possible. In this case, one relies on detecting signal in a subset of sampled spatial channels. It is important, therefore to determine the H II power spectrum of distant galaxies. This is a study waiting to be done with *HST* data by using UV continuum as a surrogate for the Hα distribution.

What is the limiting redshift for making reliable kinematic measurements? Consider the observational scenario in which one tracks a spectral feature with redshift, while increasing spatial resolution to resolve a constant physical scale. The source surface intensity per angular resolution element of this physical scale (s) is given as:

$$I = I_0(1+z)^{-3}s(z)^2,$$

where I_0 is the value at $z = 0$ per arcsec^2. Further assume that one is working in the background limited regime, but at medium spectral resolution such that the background continuum is resolved. In the optical to near infrared (0.5–1.8 μm), this continuum can be approximate as a power law in wavelength of index 2.5 (as estimated from an examination of Turnrose 1974 and Maihara et al. 1993). We can then write the background per angular resolution element, s, as:

$$B = B_0(1+z)^{2.5}s(z)^2,$$

where again B_0 is the value, per arcsec^2, for $\lambda(z = 0)$. An expression of the telescope diameter (D_T)–observing-time (t)–efficiency (ϵ) product is given as a function of S/N, source intensity, and background as follows:

$$D_T(\epsilon t)^{1/2} \propto S/NB^{1/2}I^{-1}.$$

With the above relations, we find that to achieve constant S/N per resolution element as a function of redshift yields:

$$D_T(\epsilon t)^{1/2} = (1+z)^{4.25}s(z).$$

To normalize this relation, we use the results from our survey with Haynes & Giovanelli using the Palomar 5 m telescope double spectrograph, where Hα rotation curves were measured in 1 hour (at best) for $L*$ galaxies at $z = 0.3$ through a 1 arcsec slit. This slit width subtends 4.8 kpc at this redshift ($H_0 = 70$ km s^{-1} Mpc^{-1}). To match this physical resolution at high redshift ($z > 0.7$, where the angular diameter function is relatively flat) requires 2× smaller slit width, and hence commensurately larger telescope diameter. At $z = 1$ the kinematics of the expansion add a further factor of ∼6 to the required telescope diameter.

The situation may seem pessimistic. However, one can measure rotation curves at $z \sim 1$ with a 10 m telescope in a few hours, as proven, e.g., by Vogt et al. (1997). This is done by degrading the spatial resolution (and relying on modeling of the aberrations), moving to bluer spectral features (to lower the background), and using newer spectrographs with higher efficiency. At some point the fidelity of these results should be spot-checked at significantly higher (2–3×) spatial resolution using near-infrared spectrographs coupled to adaptive optics systems now coming on

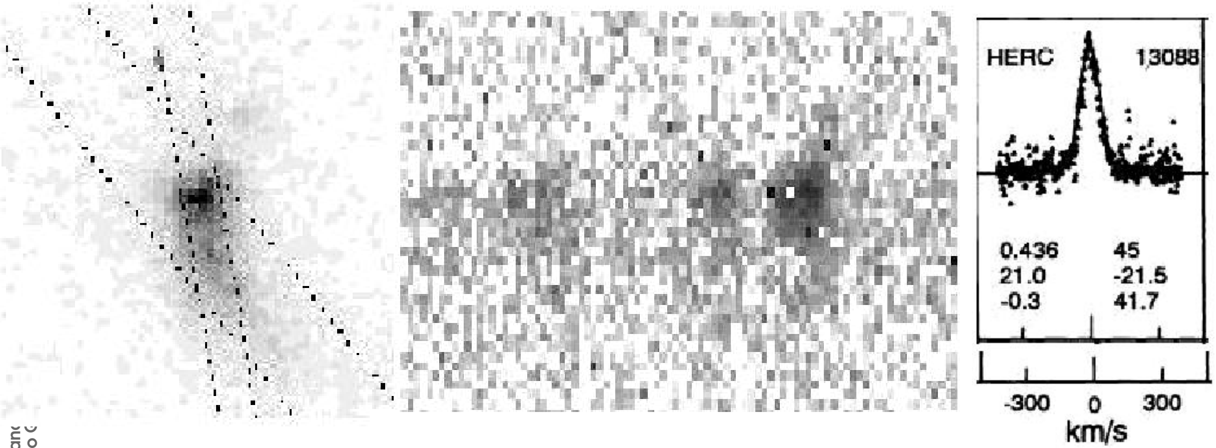

Fig. 4. An example of kinematic measurements of an intermediate redshift, luminous, compact, blue, galaxy as measured by Guzmán, Koo, and collaborators. The galaxy, Herc-1.13088, is at a redshift of $\sim$0.4. The leftmost panel is a 2×2 arcsecond cut out of an *HST* WFPC-2 I_{814} band image, showing two possible slit orientations and widths (0.2 and 0.5 arcsec) for follow-up observations with STIS. The central panel shows a preliminary extraction of the spatially resolved spectrum from STIS for the [O III] $\lambda\lambda$4959,5007 Å and Hβ lines, using the 0.2 arcsec slit width near the illustrated position angle in the left panel. The spatial dimension is in the y-direction and is roughly on the same scale as the WFPC-2 image. The rightmost panel shows the Keck HIRES (spatially *un*resolved) line width of 45 km s^{-1} (σ) using the same lines for this system (Koo et al. 1995); the source appears stellar in 1 arcsec seeing. The STIS spectrum reveals a wealth and complexity of kinematic information, which, when coupled to the WFPC-2 image, yields information as to what gives rise to the width of the spatially unresolved line. This galaxy is clearly neither a simple, axisymmetric nor a dynamically relaxed system, despite the fact that its line width appears simple, symmetric, and nearly Gaussian. A velocity field obtained via two-dimensional spectroscopy would yield additional significant clues about this systems dynamics, and aid in estimating its mass.

line. Unless one can take advantage of strong emission from unresolved H II regions (e.g., Koo's simulations), these checks will require long integrations, but they are critical measurements to make.

The situation for absorption line kinematics is even more difficult. The galaxies used to normalize the relation for D_{T}, above, have emission line equivalent widths of typically 10–40 Å. Even restricting ourselves to the observed optical portion of the spectrum with highly efficiency spectrographs, to achieve a spatially resolved absorption line kinematic measurement at $z = 1$ requires a 30 m+ telescope. However, measurements at intermediate redshifts are possible with smaller (10 m!) class telescopes, and are worthy of pursuit since stellar kinematics permit more interesting dynamical measurements, including independent estimates of disk and total mass (see, for example, Bershady et al. 2002a).

Given the length of exposures required to make reliable dynamical mass estimates at cosmological distances, we should ask: Are rotation curves enough, or should we acquire two-dimensional velocity fields? Since most high z sources do not appear to be axisymmetric systems, two-dimensional spectroscopy is critical both for making a dynamical mass determination as well as for sampling all available H II regions at high spatial resolution. Figure 4 shows an example from a sample of intermediate redshift LCBGs for which we are attempting to make both dynamical and photometric estimates of mass. The *HST*/STIS long slit spectrum reveals complex, spatially resolved kinematic structure, which is a significant improvement over the ground-based line width measurement. Nonetheless, the dynamics of this systems would be substantially easier to interpret with two-dimensional spectroscopy.

What are reasonable approaches for two-dimensional spectroscopic instrumentation to high redshift galaxies? One option is to follow the design strategy of integral field units (IFUs) or formatted field units (FFUs) used for studying galaxies in the local Universe, for example: Integral on the WHT (Arribas et al. 1998), DensePak and SparsePak on the WIYN telescope (Barden et al. 1998; Bershady et al. 2002b). Coupled to echelle spectrographs (on WIYN) these IFUs can achieve spectral resolutions of 10000–20000. These arrays have 100–200 fibers, 0.5–5 arcsec diameters, and fields of view between 10–70 arcsec. For higher redshift studies, smaller fibers are desirable. In this spirit, the GMOS IFU on the Gemini-North telescope (Allington-Smith et al. 1998) has 0.2 arcsec apertures in two arrays—a total of 1500 fibers, or roughly 10× the number then in the aforementioned instruments. With all of these fibers, however, one might consider the efficiency advantage of multiobject two-dimensional spectroscopy (MOBS), i.e., breaking down the two monolithic arrays into many independently positionable units.

The most mature example of a MOBS concept to date is the VLT (UT2) FLAMES/GIRAFFE instrument (see giraobs.obspm.fr/index-en.html and links therein), which is designed to have fifteen IFUs of twenty channels each, channel apertures of 0.52 arcsec, total aperture of 2.1 × 3.1 arcsec, and spectral resolution of 9000–29000 in the range 370–900 nm. This is a promising instrument for kinematic measurements. For future instruments, one might consider modifying the feeds and spectrograph design, however, to achieve finer spatial sampling and coarser spectral resolution. For emission line rotation curve work in the optical, one could consider dropping the spectral resolution by a factor of 1.5–5, and increasing the angular resolution by the commensurate factor (in area). This would yield something like 6000 in spectral resolution with 0.2–0.4 arcsec channel apertures (fibers or lenslets). At the other extreme, one will want to maintain the GIRAFFE IFU spectral resolution while decreasing the spatial resolution to gain adequate signal for absorption line kinematic measurements at intermediate redshifts.

Whatever the niche, one thing is clear: multiobject integral field spectroscopy offers the most efficient means of gathering information for dynamical mass estimates. Only in clusters will Fabry–Perot (or tunable filter) instruments be competitive. For field surveys, one might take further advantage of fibers and feed multiple, independently configurable spectrographs, each tuned to the redshift of the targeted galaxy. Gathering precision mass measurements even for a limited number of high redshift systems will be invaluable to calibrate mass estimates at early epochs. One might then hope to calibrate photometric mass estimates, just as we now commonly use broad band photometry to estimate redshifts.

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