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THE FORMATION EPOCH OF ELLIPTICALS AND OTHER RED-SEQUENCE GALAXIES

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RESUMEN

En preparación del muestreo GOYA con GTC/EMIR, el equipo GOYA obtuvo cuentas de galaxias profundas en las bandas U, B y Ks en el campo de Groth. Mostramos modelos de evolución de galaxias que reproducen las cuentas en las tres bandas. Los precursores de las galaxias E y S0 del Universo local tuvieron que formarse a desplazamientos al rojo $z_\mathrm{f} \sim 1.5$, para explicar el cambio de pendiente en las cuentas NIR de galaxias en $K\mathrm{s} = 17.5$. Con EMIR en GTC, planeamos observar espectroscopía en el continuo del visible en reposo, hasta $z \sim 1.5$, y el espectro de líneas de emisión, hasta $z \sim 2.6$, y obtener las propiedades de las galaxias de tipos tempranos, y sus predecesoras, en la época clave en la que dejaron de formar estrellas.

ABSTRACT

As part of the preparatory work for the upcoming GOYA Survey with GTC/EMIR, the GOYA team obtained deep galaxy number counts in the U, B and K bands, for the Groth strip. We present number count models that simultaneously explain the counts in the three bands. We find that most of the precursors of today's early-type galaxies (ellipticals, S0) must have formed at redshifts more recent than $z = 2$, with $z = 1.5$ providing a good match to the data. The constraint arises from the observed slope change that occurs in the NIR counts at $K \sim 17.5$. With EMIR on GTC, we expect to map the rest-frame optical continuum of early-type galaxies to $z \sim 1.5$, and their emission lines to $z \sim 2.6$, to obtain key properties of early-type galaxies and their precursors at the key epoch when they stopped making stars.

Key Words: **GALAXIES: ELLIPTICAL AND LENTICULAR, CD — GALAXIES: EVOLUTION — GALAXIES: FORMATION**

1. INTRODUCTION

Understanding when and how galaxies formed is a major goal of astrophysics, and indeed a goal to which GTC wants to make important contributions. We wish to understand the chronology and the physical processes that gave galaxies the properties we observe today: their diverse morphologies; their ranges of masses, sizes, gas contents, star formation activity; their density distributions, their kinematics and their nuclear activity.

Today, most galaxy formation models are based on the two-stage theory of White & Rees (1978). Dynamically-cold dark matter halos (CDM) grow hierarchically bottom-up, through a series of mergers. Baryons in the merging haloes get shock-heated to the halo's virial temperatures, then cool radiatively down to about 20 K, at which stage stars form. Cooling timescales are such that star formation occurs once the gas has dissipated onto a disk. Subsequent mergers of the parent halos redistribute the stars onto spheroids: bulges, and ellipticals.

CDM, in its current flavor ΛCDM, is successful at explaining the formation of galaxies out of the initial density fluctuations measured by the COBE satellite, and it can reproduce the large-scale distribution of galaxies (Blumenthal et al. 1984). But much work remains for explaining the chronology of galaxy formation and the detailed physics of disk and bulge growth.

Dating the formation of elliptical galaxies should provide important information to constrain CDM-based models, due to the association of ellipticals to mergers, the backbone of galaxy growth in CDM. Older ages for more massive galaxies (Thomas et al. 2005) may naively suggest anti-hierarchical growth. Color-magnitude diagram analyses of intermediate-redshift clusters suggest strongly coeval formation (Stanford et al. 1998).

The GOYA survey (Guzmán 2003), using GTC/EMIR, plans to obtain key spectral diagnostics on the population age and star formation activity of early-type galaxies at redshifts $0.5 < z < 3$. Preparatory work in recent years included a NIR and optical photometric survey, using imaging instruments on 4m-class telescopes. Here we analyze galaxy number counts derived from our imaging pro-

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gram. Our data confirm the change of slope in the NIR number counts previously reported by others (Gardner et al. 1993). Galaxy evolution models are able to reproduce such change of slope when the precursors of most of today's early-type galaxies are assumed to form at moderate redshifts, $1 < z < 2$.

2. DATA

Our NIR band number counts come from Ks-band imaging of 180 arcmin^2 of sky from the Groth field (Groth et al. 1994) and the Coppi (Coppi & Guzmán 2001) fields. Exposures of 1.5-2 hr per pointing with the WHT/INGRID camera (Hawaii-1 1024×1024 Rockwell array), and seeing ranging from 0.6″ to 1.0″, led to a depth (50% detection efficiency) of 20.6 to 21.0 Vega magnitudes. Galaxy detection and photometry were carried out with SExtractor (Bertin & Arnouts 1996). Inferred counts were duly corrected from detection efficiency, spurious detections, foreground extinction and star counts. The counts are presented and analyzed in Cristóbal-Hornillos et al. (2003, hereafter CH03).

U- and B-band galaxy counts come from our imaging of the Groth strip with the INT/WFC instrument. An area of 0.29 square degree was covered with exposures of 4 hr and 3 hr in U and B, respectively, reaching 50% detection efficiencies of 24.8 mag and 25.5 mag (Vega system). Corrections were applied to the counts as described in the previous paragraph. See Eliche-Moral et al. (2006, hereafter EM06) for details. The final B and Ks counts are depicted in Figs. 1 and 2, Prieto et al. (these proceedings).

3. MODELS

The change of slope in the Ks counts is readily visible. We measured logarithmic slopes of $\gamma \equiv d\log N/d\,\mathrm{mag} = 0.59$ brightward of $K\mathrm{s} = 17.5$, and $\gamma = 0.25$ faintward. A slope of $\gamma = 0.60$ is expected of a uniform distribution of sources in an Euclidean Universe.

We ran number count models using the ncmod code (Gardner 1998). ncmod simply evolves the local luminosity function (LF) back in time according to the prescriptions of population synthesis models. This modeling is appropriate since such an abrupt feature in the number counts as is seen in the Ks counts must be related to a strong change in the luminosity function at some look-back time. Details of the models are given in EM06. Briefly, the models are anchored at $z = 0$ to the morphologically-dependent LF's from SDSS (Nakamura et al. 2003), and evolved back in time using the 2003 Bruzual & Charlot models (Bruzual & Charlot 1993). Four galaxy classes are considered, namely ellipticals and S0's; early spirals; late spirals; and irregulars. A merger-driven, luminosity conserving number evolution is assumed, that scales as $(1 + z)^{2.0}$. Assuming extinction ($\tau_B = 0.6$) for all galaxy classes is essential in order to fit the blue bands. Other modeling parameter have a minor contribution to the final results.

Extensive testing led to the conclusion that the only way to reproduce the downward change in the Ks count slope is to delay the formation of a dominant population to moderate redshifts. Early-type galaxies must be the culprits as they dominate the Ks counts at $z = 0$. While in U or B it is comparatively easy to break a power-law behavior by playing with extinction, or star formation activity, both of which strongly modify the UV continuum emission of galaxies, for the Ks counts only a drastic z-evolution of the galaxy numbers can break the power-law behavior of the counts, given the weak effects of dust extinction in Ks, the small K-corrections and the slow sensitivity of M/L_K to star formation episodes. Our model is able to reproduce the $K\mathrm{s} = 17.5$ slope change *and* the lack of such feature in the blue passbands by assuming a formation redshift of $z_\mathrm{f} = 1.5$ for the precursors of ellipticals and S0's. The model predictions, shown in Figs. 1 and 2 of Prieto et al. (these proceedings), successfully reproduce ranges of 16 mag in U (not shown), 18 mag in B, and 10 mag in Ks. The $z_\mathrm{f} = 1.5$ for early types gives the $K\mathrm{s} = 17.5$ knee; extinction prevents the knee from appearing in the blue passbands; and, number evolution gives the overall right slope; thanks to the assumed number evolution, we find no need to introduce a disappearing population of dwarfs at intermediate redshifts.

4. FORMATION OF EARLY TYPES

The knee in the Ks counts, if indeed related to a major epoch of formation of early types, constraints the time of such formation to $1 < z < 2$. E.g., setting $z_\mathrm{f} = 2.5$ for ellipticals and S0's leads to a clear mismatch with the data.

Our result applies to the dominant elliptical population. Some elliptical formation at earlier times is compatible with the data, as is residual elliptical formation at $z < 1$, but the present modeling cannot put strong limits to these fractions, or on the presence of downsizing.

Our $z_\mathrm{f} = 1.5$ result (age 9 Gyr) is in excellent agreement with recent inferences on the formation epoch of ellipticals. After correcting for 'progenitor bias', van Dokkum & Franx (2001) infer $z_\mathrm{f} = 2.0^{+0.3}_{-0.2}$, which is consistent with our result. Thomas et al. (2005) conclude $1 < z_{\rm f} < 2$ outside cluster environments (and $z_{\rm f}$= 3 to 5 in dense environments). Morphology studies also support our inferred formation epoch. Cassata et al. (2005) conclude that ellipticals are not present at $z = 2$ in the K20-GOODSS sample.

In contrast, the formation redshift for early-type spirals is much less constrained by the data: $z_{\rm f}$ in the range 1 to 4 yields moderately good matches to the UBKs counts. We obtain further clues on the $z_{\rm f}$ for early-type spirals by looking at an observable that is independent from the counts – the color distributions. Simple evolution models such as NCMOD are known to yield too narrow color distributions as compared to data (Gardner 1998). Our modeling relates this problem to the assumption of a single formation epoch for each galaxy class. By assuming a range of $z_{\rm f}$ from 1 to 4, models tend to reproduce the width of the observed color distributions.

5. EMIR

EMIR on GTC will be the ideal instrument to further characterize the star-formation activity, and its cessation, in early-type galaxies. Star formation will be traced through the Hα emission line, over the entire wavelength range of EMIR, up to $z \sim 2.6$. Absorption-line diagnostics, i.e. stellar velocity dispersions, metallicities, and α-enhancements, will probably be restricted to $z < 1.5$ and need tens of hours of integration as they require mapping the continuum with moderate S/N$\sim$ 20: the project will be feasible thanks to a close coordination with other areas of the GOYA survey. Key to the strength of the resulting science will be a strict sample selection based on as red a band as possible - observed K-band, and, where available, rest-frame K-band from Spitzer surveys.

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