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GALAXY SURVEYS IN THE ERA OF LARGE GROUND-BASED TELESCOPES

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RESUMEN

Reseño las estrategias observacionales y los resultados recientes de varias exploraciones galácticas en una amplia gama de corrimientos al rojo, en la nueva era de los grandes telescopios en tierra. Estas exploraciones se comparan con dos exploraciones mayores de galaxias que actualmente se proponen para el GTC: OTELO y COSMOS. Las dos exploraciones están enfocadas a una región del espacio de parámetros observacionales que todavía no ha sido explorada en forma extensa. Concluyo que a pesar del arribo tardío del GTC, OTELO y COSMOS son muy competitivos y podrán asegurar un aprovechamiento científico de primera clase para el GTC, pero únicamente en el caso de que se asigne a estas exploraciones una cantidad sustancial de tiempo observacional y de recursos.

ABSTRACT

I review the observing strategies and recent results of various galaxy surveys over a wide range in redshift in the new era of large, ground-based telescopes. These surveys are compared to two major galaxy surveys currently being proposed for the GTC: OTELO and COSMOS. Both surveys focus on a region of the observational parameter space that has not been explored extensively yet. I conclude that, despite the late arrival of the GTC, OTELO and COSMOS are very competitive and will ensure a top-class scientific return for the GTC, but only if a substantial amount of observing time and resources are allocated for such surveys.

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

1. INTRODUCTION

Galaxy surveys at different redshifts provide the necessary data to:

- carry out a comprehensive census of the galaxy population in a representative volume of the universe at different epochs.
- study galaxy formation and evolution by providing direct observations to shed light on the formation epoch of the different galaxy components (e.g., measuring the morphology, size, light profile, or bulge-to-disk ratio of galaxies at high redshifts), the role of the environment (field, pairs, groups or clusters), the rate and mechanism of assembly of the massive galaxies we see today (via hierarchical mergers or monolithic collapse), the origin of scaling laws (such as Tully-Fisher or the Fundamental Plane), the history of star formation and chemical enrichment, or the relation to other astronomical phenomena such as AGN, Gamma-ray bursts, etc.
- probe the large scale structure and the nature of dark matter using power spectrum analysis of the three-dimensional distribution of luminous matter in the universe, and gravitational lensing by galaxy clusters or galaxy peculiar velocities to map the distribution of dark matter.
- measure cosmological parameters using galaxy properties such as age, size, luminosity, surface brightness, merger rate, or cluster density, as probes to test various cosmological models.

Galaxies provide not only information about the main constituents of the universe but also test particles to trace the properties of the universe as a whole. One of the main difficulties in galaxy surveys is the problem of getting enough information to assemble a global, representative picture of the universe. Gathering a body of data large and accurate enough to be useful in addressing the broad range of astronomical goals summarized above is the starting point of any major survey. Before the advent of 10m-class telescopes, photometric surveys focused on the study of morphologies, colors, and luminosities gathered samples of as much as $\sim 10^4$ galaxies at $z < 0.1$, and $\sim 10^3$ galaxies at $0.1 < z < 1.5$. Spectroscopic surveys in turn produced samples as large as $\sim 10^3$ galaxies at $z < 0.1$, and only $\sim 10^2$ galaxies

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at $0.1 < z < 1.5$ to study galaxy ages, star formation rates (SFRs), metallicities, and kinematics. About a decade ago, there were almost no galaxies known at redshifts $z > 1.5$. With the new generation of large ground-based telescopes and wide-field instrumentation, the typical samples of current galaxy surveys, including both photometric and spectroscopic properties, are three orders of magnitude larger than previous surveys over the same redshift range. In addition, the universe at $z > 1.5$ is now being systematically surveyed with samples of about $10^3 - 10^4$ galaxies, which include measurements of morphologies, colors, luminosities, ages, SFRs, metallicities, and kinematics. We live in an era where observations have a leading edge over theoretical models, and their input is now indispensable to advance theoretical efforts.

2. OVERVIEW OF CURRENT GALAXY SURVEYS

Over the last decade, several large collaborations have been put together world-wide to carry out the new generation of galaxy surveys. Three main characteristics distinguish galaxy surveys in this new era of large, ground-based telescopes: (i) guaranteed access over a long period of time to state-of-the-art wide-field instruments specifically designed for these surveys; (ii) galaxy samples that are 2-3 orders of magnitude larger than any previous work on the field, and can be considered for the first time to be statistically representative of the universe at a given epoch, and (iii) large, homogeneous datasets including a wide variety of photometric and spectroscopic parameters measured to an unprecedented degree of accuracy and over an unprecedented range in redshift.

Representative examples of such galaxy surveys in the low redshift regime are the Sloan Digital Sky Survey (SDSS, http://www.sdss.org), which has a dedicated 2.5-m telescope equipped with a wide-field optical camera and spectrograph, or the Two-Degree Field Galaxy Redshift Survey (2dfGRS, http://www.aao.gov.au/2df/), which has been a key-project on the 4m AAT during 7 years using the 2df optical multifiber spectrograph. Both of these surveys aim at characterizing the properties of the general galaxy population and their relationship with the galaxy environment, and mapping the three-dimensional distribution of matter to a distance of about $z = 0.2$ using spectroscopic observations of $\sim 10^6$ galaxies down to 19 mag (Gunn & Knapp 1993; Colless 1999).

At intermediate redshifts ($z < 1.5$), there are two main surveys currently being conducted: the Deep Evolutionary Extragalactic Probe (DEEP, http://deep.ucolick.org), and VIMOS VLT Deep Survey (VVDS, http://www.astrsp-mrs.fr/virmos). The DEEP collaboration has been granted at least 30 nights in 4-m class telescopes to obtain the deep BRIK photometry necessary for the sample selection. In addition, DEEP has been awarded 120 nights at Keck using DEIMOS. The VVDS collaboration in turn has been granted 45 nights in 4-m class telescopes to prepare the sample selection, and has been awarded at least 70 nights at the VLT using VIMOS. DEIMOS and VIMOS represent the state-of-the-art in wide-field optical multi-object spectrographs available today in 10-m class telescopes, and were built specifically by the DEEP and VVDS teams, respectively, to carry out these surveys. The main scientific goals of the DEEP and VVDS surveys are very similar: to map the distribution of galaxies, AGN and large-scale structure, and parameterize their evolution over the last 8 Gyrs using spectroscopic measurements of $\sim 10^5$ galaxies down to 24 mag (Koo 1998, Le Fevre et al. 2004). A distinguishing aspect of DEEP, however, is their ability to study the internal kinematics of the distant galaxy population due to the higher spectral resolution of DEIMOS. Such internal kinematics provide a powerful new dimension related to the dynamical masses of galaxies. These are intimately tied to dark matter halo masses, which in turn are the fundamental components of galaxies best understood from theoretical simulations. In addition, internal kinematics can be used as a standard volume tracer for testing the various cosmological models and to investigate the origin and evolution of the galaxy scaling laws.

The systematic exploration of high redshift galaxies ($z > 1.5$) is a relatively recent area of research. In this regard, it is necessary to mention the pioneer work by the collaboration led by Chuck Steidel, which has been awarded about 30 nights in 4-m class telescopes to obtain the deep optical photometry for the sample selection, and between 75 and 100 nights at Keck and VLT for the optical and near-IR spectroscopic follow-up (http://www.astro.caltech.edu/ccs/). However, the most ambitious survey of the distant universe to date is the Great Observatories Origins Deep Survey (GOODS, http://stsci.edu/ftp/science/goods). This survey has been awarded a Spitzer Legacy Program, which will provide deep photometry at 3.6 to 24 microns with IRAC/MIPS, and a HST Treasury Program, which will provide deep optical photometry with ACS. In addition, it has assured an "extensive commitment" by ESO and NOAO on 4-

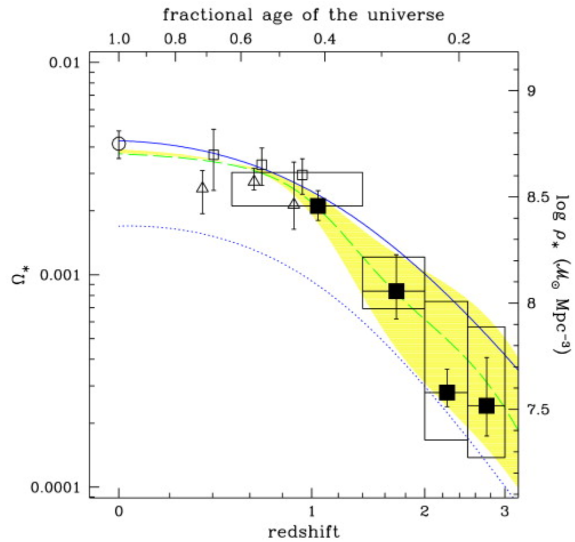

Fig. 1. Redshift evolution of the comoving stellar mass density (reproduced from Dickinson et al. 2003). Open symbols show results at $0 < z < 1$ (circle, Cole et al. 2001; triangles, Brinchmann & Ellis 2000; squares, Cohen 2002; filled squares, HDF-N points). The vertical extent of the boxes shows the range of systematic uncertainty introduced by varying the metallicity and the SFR of the mass-fitting models used. The solid and dotted curves show the result of integrating the cosmic SFR history, traced by rest-frame UV light, with (solid) and without (dotted) corrections for dust extinction). The dashed curve shows the integrated SFR history from Pei et al. (1999), with their 95% confidence range indicated by the shaded region.

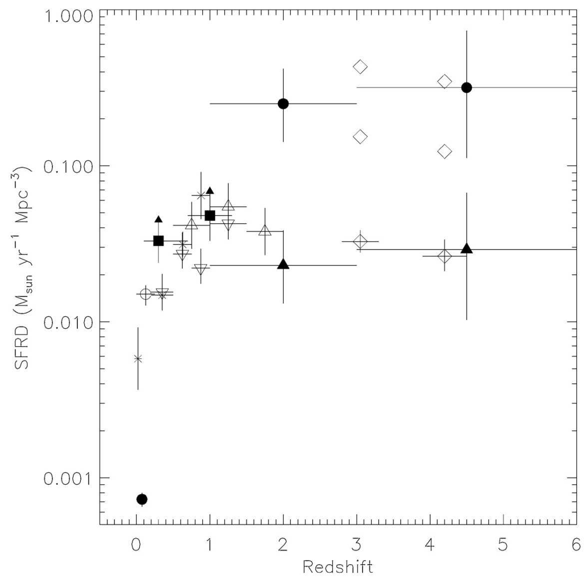

Fig. 2. Star-formation density traced by a variety of star-forming galaxies at different redshifts (reproduced from Barger et al. 2000). The open diamonds with error bars are the data points at $z = 3 - 4$ of Lyman-break galaxies with no dust correction included (Madau et al. 1998). The filled triangles and circles are SCUBA galaxies. The two sets of open diamonds with no error bars represent two different estimates of the dust obscuration correction for the Lyman-break galaxies.

m and 10-m class telescopes to obtain deep optical and near-IR photometry and spectroscopy. Optical surveys of high redshift galaxies use the broad-band "dropout" technique to identify the Lyman-break spectral feature in galaxies at redshifts $z > 2.5$. The data collected so far have been used in a number of pioneering investigations on the nature of the Lyman-break galaxy population at high redshift, their large-scale distribution, their contribution to the star formation history of the universe, and their relationship to the diffuse intergalactic medium (Steidel et al. 2003; Dickinson et al. 2003).

A detailed account of all the scientific results achieved by these and other similar surveys is well beyond the scope of this paper. The readers are referred to the web pages referenced above where they can find a complete relation of all papers published by each collaboration as well as an update of the most recent results. For the purpose of this paper, I would simply like to highlight four key areas of research common to all major current galaxy surveys:

- *Mass Assembly*: In current models of structure formation, dark matter halos build up in a hierarchical process controlled by the nature of the dark matter, the power spectrum of the density fluctuations, and the parameters of the cosmological model. The assembly of the stellar content of galaxies is governed by more complex physics, including gaseous dissipation, the mechanics of star formation itself, and the feedback of stellar energetic output on the baryonic material of the galaxies. The total, integrated mass in stars is tightly coupled to the history of star formation, as traced by the infrared background, and to the cold gas content of the universe. Reducing the uncertainties on all of these measurements will provide strong constraints on models for galaxy formation. A summary of the current measurements of the stellar mass density at various epochs is shown in Figure 1 (Dickinson et al. 2003).

- *SFR Density of the Universe*: By modeling the "emission history" of the universe at ultraviolet, optical, and near-infrared wavelengths from the present epoch to $z \sim 4$, it is possible to

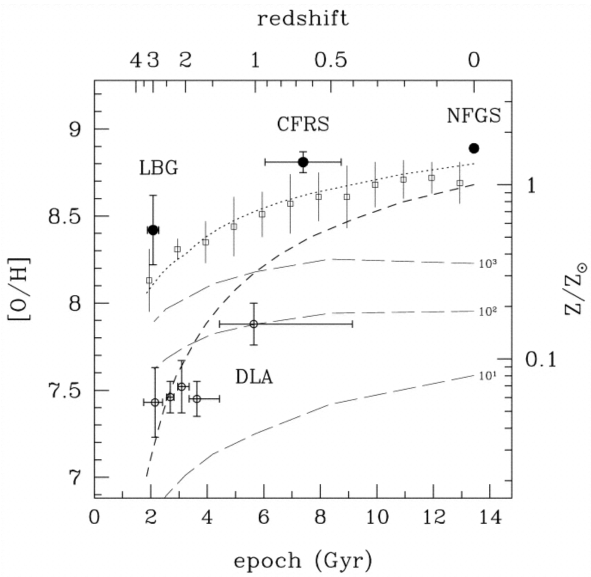

Fig. 3. Estimates of metallicity over cosmic time (reproduced from Lilly et al. 2003). The heavy solid symbols represent [O/H] metallicities (left-hand axis) at three cosmic epochs derived in a self-consistent way from R23 using the data for the NFGS in Jansen et al. (2000), Lilly et al. (2003), and Pettini et al. (2001). The light open circles are Damped Lyman Alpha absorption systems and are based on [Fe/H] metallicities (right-hand axis) in the column density weighted analysis of Kulkarni & Fall (2002). The evenly spaced open squares are the [Fe/H] age-metallicity relation for the Galactic disk from Twarog (1980). The lines represent various theoretical models: the global model from Pei et al. (1999; short-dashed line), the collisional starburst model from Somerville & Primack (1999; dotted line), and three cuts of overdensity from the numerical simulations of Cen & Ostriker (1999; long-dashed lines).

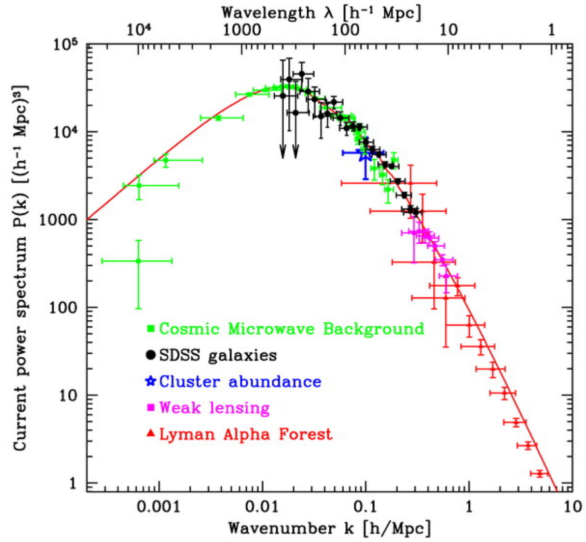

Fig. 4. Characterization of the SDSS power spectrum in terms of constraints on the "shape parameter" $h\Omega_m$ and the baryon fraction f_b (reproduced from Tegmark et al. 2004). The best to the power spectrum supports the so-called "concordance cosmology", i.e., a lambda-dominated universe.

answer some key questions in galaxy formation and evolution studies. For instance: is there a characteristic epoch of star and metal formation in galaxies? What fraction of the luminous baryons observed today were already locked into galaxies at early epochs? Are high-z galaxies obscured by dust? Do spheroids form early and rapidly? Is there a universal IMF? (Madau et al. 1998). A summary of the current understanding of the history of the star formation activity of the universe is illustrated in Figure 2 (Barger et al. 2000).

- *Cosmic Chemical Evolution*: The metallicity of the universe and of objects in it provides a fundamental metric reflecting the development of structure and complexity in the universe on galactic scales. This metric is all the more important because it is relatively easily observable and "long-lived" in the sense that heavy atomic nuclei, once produced, are not readily destroyed. The metallicity of a galaxy can only increase monotonically with time (unless large-scale infall of primordial gas is invoked), while other parameters such as the luminosity may increase or decrease depending on the instantaneous SFR. Metallicity is thus less sensitive to variations because of transient star formation events in a galaxy's history and provides a good tracer of the overall evolution of the stellar populations. A summary of the current estimates of the metallicity evolution as a function of redshift is shown is Figure 3 (Lilly et al. 2003).

- *Large Scale Structure*: The cosmological constraining power of three-dimensional maps of the universe provided by galaxy redshift surveys has motivated ever more ambitious programs to measure the shape of the real-space matter power spectrum P(k) as a function of redshift. Analysis of the 2dFGRS and SDSS datasets has corroborated the dark energy-dominated cosmology first suggested by the SN-Ia results and later supported by the WMAP measurements. A summary of all latest measurements of P(k) at various scales is shown in Figure 4 (Tegmark et al. 2004).

3. GALAXY SURVEYS WITH THE GTC

When GTC sees its first-light in 2005, it will have to compete with other 10m-class telescopes that have been fully operational for over a decade. In the previous section, I have emphasised the large amount of work already being undertaken by several international collaborations to survey galaxies over a large redshift range. A fair question to ask is: "can the GTC be competitive in the area of galaxy surveys?". My answer to this question is a clear "YES!", but only if the new GTC galaxy surveys are unique. In my opinion, this can be achieved if the following two conditions apply: (i) the GTC surveys focus on an unexplored region of the observational parameter space, either by studying a completely different galaxy sample (e.g., using different selection criteria), or by studying a different set of properties (e.g., observing at a different wavelength range); and (ii) the GTC instruments are optimally designed to conduct such galaxy surveys. There are currently two major galaxy surveys that are being proposed for the GTC that fulfill the two conditions above.

3.1. *OTELO*

OTELO is a flux limited survey of emission line galaxies in large and perfectly defined volumes of the Universe using OSIRIS (see contributions by J. Cepa, J. Gonzalez, and J. Gallego in these proceedings). The redshift range of interest is $0.24 < z < 6.6$. The estimated sample size is $\sim 10^4$ galaxies and AGNs. The main scientific goals are: (i) to measure the SFR density of the universe using Hα luminosities at $0.24 < z < 0.5$ (cf. Figure 2); (ii) to parameterize the chemical evolution of the universe from $z = 0.24$ to $z = 1.5$ (cf. Figure 3); and (iii) to detect Lyα emitters at $z = 5.7, 6.6$ (Cepa et al. 2003).

The originality of this survey rests on the sample selection. It uses tunable filters, a key feature of OSIRIS compared to similar instruments in other 10m-class telescopes, to do co-moving tomography at a depth that allows to measure fainter emission line galaxies than those studied by previous surveys, while scanning volumes of the Universe that contain statistical representative samples. OTELO is ideally suited OSIRIS, a first generation instrument for the GTC which was designed with this project in mind as the main science driver. More information about OTELO can be found in: *www.ll.iac.es/proyect/OSIRIS/OSISCI/osiotelo.html.*

3.2. *COSMOS*

COSMOS[2] is a magnitude-limited survey of the galaxy population at very high redshifts using EMIR (see contributions by M. Balcells, J. Gallego, R. Pello, and T. Contini in these proceedings). The redshift range of interest is $z > 1.5$. The estimated sample size is $\sim 10^3$ galaxies. The main scientific goals are two-pronged. Firstly, COSMOS aims to provide a comprehensive understanding of the nature of galaxies at $2 < z < 3$ and assess their evolution over cosmological timescales by comparing directly their rest-frame optical properties with those of the galaxy population in the nearby universe. In particular, the rest-frame wavelength range will provide direct determinations of the amount of extinction in high redshift galaxies –one of the most controversial corrections in current studies– using the Balmer decrements technique, the SFR density of the universe at $2 < z < 3$ by measuring Hα luminosities (cf. Figure 2), and the chemical enrichment of the universe at $2 < z < 3$ by measuring the Oxygen abundance (cf. Figure 3). A most novel aspect of COSMOS will be its ability to study the internal kinematics of high redshift galaxies by measuring the emission line velocity widths. As it was mentioned earlier, internal kinematics provide a powerful new dimension related to the dynamical masses of galaxies, which in turn serve as tracers of the dark matter halo masses which are being modelled by the new generation of theoretical simulations (Guzmán 2003). Secondly, COSMOS will be able to search for primeval galaxies at the earliest epoch of the universe through observations of OII[3727] up to $z = 5.4$ and Lyman alpha at $z > 10$ (Guzmán 2003).

The originality of this survey rests on the wavelength range of study. At $z > 1.5$, the rest-frame wavelength range is shifted into the near-IR. Only a near-IR multiobject spectrograph in a 10-m class telescope can provide the efficiency and sensitivity required to carry out a survey like COSMOS. To date, such instrument does not exist. COSMOS first came to light as the main science driver behind EMIR at the GTC, one of only two near-IR multiobject spectrographs for 10-m class telescopes currently being built in the world. The second such instrument is FLAMINGOS-2 which is being built at the University of Florida for GEMINI-S. However, the higher spectral resolution of EMIR will allow not only a higher efficiency in observing the emission lines of

[2] To avoid confusion with the HST COSMOS program led by Nick Scoville, the COSMOS survey was renamed "GOYA" (The **G**alaxy **O**rigins and **Y**oung **A**ssembly Survey) at this meeting.

high redshift galaxies between the forest of OH sky lines, but also to conduct the unique survey of internal kinematics and dynamical masses at a very early period in the history of the mass assembly of galaxies in the universe (cf. Figure 1). Finally, since a large fraction of star-forming galaxies at $z > 1.5$ behave as "standard candles" following the same scaling law between Hβ luminosity, velocity width, and Oxygen abundance defined by nearby HII galaxies, it is possible to use them to perform the classical redshift-distance test and constrain cosmological models with maximum discrimination between the various cosmological parameters (Siegel et al. 2004). A more detailed description of COSMOS can be found at: *www.ucm.es/info/emir/cosmos.*

4. CONCLUSIONS

In this paper I have argued that the GTC can still develop a world-class scientific program in the area of galaxy surveys if the proposed GTC surveys focus on an unexplored region of the observational parameter space, and the GTC instruments are optimally designed to conduct such surveys. Two surveys, OTELO and COSMOS, are ideally suited to take advantage of the unique capabilities of the first generation of wide-field instruments at the GTC: OSIRIS and EMIR. However, for any GTC survey to be able to compete successfully with the major surveys that are currently being conducted in all large ground-based observatories, it is essential that GTC grants them a "Key Project" status. All large ground-based and space observatories today have Key Projects which, in essence, are simply large surveys of faint populations. Survey mode is arguably the most efficient use of the high sensitivity and wide field of view characteristic of the new generation of large ground-based telescopes. Indeed, key projects are becoming the gold-standard of research in astronomy at the dawn of this XXI century, providing the largest scientific impact and the fastest advance of knowledge in a particular area of research.

In my opinion, a successful key project needs:

- a scientific program that is both unique and specifically tailored to the characteristics of the telescope and its instrumentation.

- guaranteed observing time, essential both to conduct the preparatory groundwork and the actual project. If the access to the required instrumentation till the survey completion is not guaranteed, delays due to technical problems, bad weather, and changing Time Allocation Committees will jeopardize the survey timely competitiveness and condemn it to failure.

- a fast, reliable data reduction pipeline to promptly reduce and analyze the sometimes overwhelming amount of data produced by the new generation of wide-field instruments in survey mode.

- adequate resources in manpower, equipment, and funding.

- to provide an easy-access, fully-reduced database for use of the entire community.

In summary, large ground-based telescopes have been fully operational for over a decade, and several major galaxy surveys are currently underway. In order to compete in this field, GTC will have to make a decisive impact in those areas of research that have not yet been fully explored by other 10-m class telescopes. This can be best done by conducting key projects that best take advantage of the unique instrumentation of the GTC, such as the OTELO and COSMOS surveys. I am convinced that the scientific return of such surveys will allow GTC to claim its own place among the world-class large observatories.

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