A NICMOS SEARCH FOR HIGH-REDSHIFT ELLIPTICAL GALAXY CANDIDATES

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ABSTRACT

We have collected optical follow-up observations from the ground and the Hubble Space Telescope (HST) for 13.74 arcmin² of archival images taken with the HST Near-Infrared Camera and Multiobject Spectrograph (NICMOS). We use two criteria to select E/S0 galaxy candidates at $z \approx 1$ and $z \approx 1.5$ (high-redshift elliptical candidates [HzECs]) based on colors and infrared morphology. The observed surface density of HzECs is significantly smaller than what is predicted assuming the local luminosity function (LF) of E/S0, constant comoving density, and pure passive evolution with a high redshift of formation of the stellar populations ($z \approx 5$). On the other hand, assuming a low redshift ($z \approx 2$) of formation, not enough HzECs are predicted. The data are very well matched assuming that a substantial fraction of present-day E/S0’s (10%–66%, depending on cosmology and on the local LF of E/S0’s) formed at $z \approx 3$ or higher and then evolved passively. The rest of the current E/S0 population may have formed at lower redshift or may have been rejected by the selection criteria because of interactions or more recent episodes of star formation (disturbed morphology and/or bluer colors).

Subject headings: cosmology; observations — galaxies; elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — infrared: galaxies

1. INTRODUCTION

The formation of elliptical galaxies is still not understood. In a schematic view, all the different models can be summarized within two simple paradigms: (1) the monolithic collapse, in which elliptical galaxies form at high redshift in short bursts of star formation; and (2) the merging scenario, in which they form at lower redshift by merger of disk galaxies.

In recent years, many observational programs have started to provide useful constraints on theoretical models. Studies such as MORPHS, a Hubble Space Telescope (HST) survey of intermediate-redshift clusters (up to $z \approx 0.5$; e.g., Ellis et al. 1997), or the investigation of the fundamental plane of elliptical galaxies at intermediate redshift in clusters (van Dokkum et al. 1998) and in the field (Treu et al. 1999), indicate that the bulk of star formation occurred at $z \approx 1$. However, low-redshift ($z \lesssim 1$) diagnostics are mostly sensitive to the epoch when stars were formed rather than to that when galaxies were assembled (see, however, Lilly et al. 1995; Kauffmann, Charlot, & White 1996). Unfortunately, it is in their predictions on the latter that galaxy formation models differ the most. Thus, the most direct and uncontroversial way to break the degeneracy is to push the investigation to higher and higher redshift, trying to put limits on the number of already-assembled (proto-)elliptical galaxies. The Near-Infrared Camera and Multiobject Spectrograph (NICMOS) parallel images can provide a decisive breakthrough onto this issue. In fact, high-redshift elliptical galaxies appear extremely red in their optical-infrared colors (e.g., Spinrad et al. 1997), and morphological information is the best way, short of spectroscopic identification, to distinguish between high-redshift old stellar populations and reddened dusty starbursts (e.g., Graham & Dey 1996; Stiavelli et al. 1999).

By using the NICMOS parallel images combined with deep optical images, both from ground-based telescopes and with the Wide Field and Planetary Camera 2 (WFCPC2) on HST, we have undertaken a survey (13.74 arcmin²) to determine the number of elliptical galaxies already assembled at $z \approx 1$. The aims of the survey, the selection criteria, and the sample are described in § 2. The building of the catalog is briefly discussed in § 3. The results and conclusions are discussed in § 4. A more detailed description of the data reduction and the complete catalog of the selected sources, together with images, surface photometry, and photometric redshifts, will be given elsewhere (Treu & Stiavelli 1999, hereafter Paper II).

AB magnitudes (Oke 1974) are used throughout the Letter. The HST filters are indicated as $H_{160}=F160W$ and $I_{111}=F110W$ (NICMOS) and $J_{111}=F814W$ and $V_{606}=F606W$ (WFCPC2). $H_0$ is assumed to be 100 km s⁻¹ Mpc⁻¹. The present value of the matter density and the cosmological constant are indicated by $\Omega$ and $\Omega_\Lambda$, respectively.

2. THE SURVEY

Due to the effect of redshift and the lack of UV emission in old stellar populations, elliptical galaxies at $z=1−2$ are relatively bright in the IR, but they are faint in the optical. For example, a single-burst model of solar metallicity (Bruzual & Charlot 1993 [GISSEL 96 version]) with Salpeter initial mass function and cutoffs at 0.1 and 100 $M_\odot$, normalized to a luminosity of $M_V = -21.0$ at 15 Gyr (roughly $M_\odot$), at 2 Gyr and $z = 1.5$, has $H_{160} = 21$, $J_{111} = 22$, $I_{111} = 23.7$, $R = 25.3$, and $V_{606} = 26$, assuming $\Omega = 0.3$ and $\Omega_\Lambda = 0.7$. For this reason, high-redshift elliptical galaxies can constitute a significant fraction of the so-called extremely red objects (EROs). Unfortunately, even the best color-based classification suffers from the degeneracy between old stellar populations and dusty starbursts. High-resolution imaging holds the key to classify these objects properly, since many EROs are so faint that their continuum cannot be detected spectrosopically, even with 8–10 m telescopes. For example, the nature of the two best-known EROs

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⁴ See also http://icarus.stsci.edu/˜treu/HizECs.
with spectroscopic information is fully revealed by their morphology: (1) HR 10, a dusty starburst at $z = 1.44$ (Dey et al. 1999; Cimatti et al. 1998) is distorted in the $H$ band images, while (2) LDSS 53091 is smooth and shows a perfectly regular light profile (Dunlop 1998). From the statistics of EROs we know that the density of high-redshift elliptical galaxies ($z \geq 1$) must be of the order of 1 arcmin$^{-2}$, the precise value depending on the definition and the magnitude limit (e.g., Thompson & Beckwith 1998; Cohen et al. 1999; Yan 1999).

For all these reasons, the essential ingredients for a successful search for high-redshift elliptical galaxies are as follows: (1) High-resolution IR imaging. The morphology is best studied in the IR, where sources are brighter and the surface brightness is a better tracer of the mass distribution and is less affected than the optical by, e.g., a dwarf galaxy companion or an otherwise negligible amount of star formation. (2) Medium deep IR imaging, since the galaxies we are looking for are expected to be in the range $H_{\alpha} = 20–24$. Deeper images would probe a wider range of the luminosity function, but it would be difficult to measure the flux of the optical counterparts. (3) The largest possible area.

### 2.1. Selection Criteria

In order to count high-redshift elliptical candidates (HizECs) properly, we need a definition excluding as much as possible galactic stars and dusty star-forming objects. We require the object to be clearly resolved, i.e., $FWHM \geq 0^\prime 3$, hence having a scale length $\geq 3$ kpc, depending on the redshift and the cosmological parameters; (2) to appear roundish and regular, with no spikes, tails, or knots; and (3) to have colors consistent with a Bruzual & Charlot (1993; GISSEL 96 version) model of old stellar populations ($\geq 1$ Gyr) at $z \geq 1$. In order to quantify the third criterion, we have computed the observed colors of a range of models as a function of redshift. For a given cosmology and metallicity, we computed the colors of a passively evolving stellar population formed at redshift $z = 10$ and of a 1 Gyr old single-burst stellar population. These two cases represent the red and blue extremes of the objects we want to select and therefore bracket the possible cases.

Based on the computed colors, we define a broad and a narrow selection criteria. The broader criterion, tuned to collect all the elliptical candidates at $z \geq 1$, is $I_{606} - H_{16} > 1.8, I - H_{16} > 1.9, R - H_{16} > 3.2$, and $V_{606} - H_{16} > 3.8$. The more stringent criterion, tuned to $z \geq 1.5$, is defined by $I_{4625} - H_{16} > 2.7, I - H_{16} > 2.8, R - H_{16} > 4.0$, and $V_{606} - H_{16} > 4.5$. Since the $J_{11} - H_{16}$ color is much smaller, and therefore more affected by photometric (of order of $0.2–0.3$ mag) and modeling errors, we do not include it in the color selection criterion, but we shall use it, when available, as a consistency check.

Extremely high redshift galaxies can appear very red when Ly$\alpha$ forest absorption (Madau 1995) starts to affect the $V_{606}$ and $R$ filters. Nevertheless, the colors of extremely high redshift galaxies can easily be distinguished from those of an old stellar population at $z = 1–2$ because the cosmic transmission falls blueward of 1215 Å much more sharply than the expected HizEC spectral energy distribution (Madau et al. 1996). Furthermore, galaxies at $z \geq 6$ would need to be enormously bright in order to be detectable at $H \sim 24$ (Chen, Lanzetta, & Pascale 1999; Weymann et al. 1998). Therefore, we assume the contamination to our sample of HizECs by extremely high redshift galaxies to be negligible.

#### 2.2. The Sample

In order to survey the largest possible area, we collected data from different sources:

1. The pointings of the $HST$ NICMOS parallel data taken with NIC3 through F160W were cross-correlated with the entire WFPC2 and Space Telescope Imaging Spectrograph (STIS) archive, looking for intentional or serendipitous overlaps with WFPC2 red or STIS clear images. Only overlaps with $I_{606}$ and $V_{606}$ were found. We selected the fields with exposure time greater than 1000 s. Fields with galactic latitude $|b| < 10^\circ$ or $E(B-V) > 0.15$ (according to Schlegel, Finkbeiner, & Davis 1998) were discarded to reduce intervening reddening or foreground star contamination. Fields with $H$ filaments or with the primary target extended enough to enter the parallel field of view were discarded as well.

2. Deep optical $R$-band imaging of two NICMOS parallel fields was obtained at the ESO New Technology Telescope (NTT) using the Superb Seeing Imager 2 (SUSI2) under superb seeing ($0^\prime 5–0^\prime 6$ measured on the combined image). The $3\sigma$ limiting magnitude over a 1 arcsec$^2$ area is $R = 26.8$.

3. The optical counterparts for the Hubble Deep Field South (HDFS) NICMOS flanking fields made available by Teplitz et al. (1998). We also used the $R$- and $I$-band images of Tru et al. (1998).

4. The NICMOS catalog of part of the Hubble Deep Field (HDF; Thompson et al. 1999) was cross-correlated with the HDF WFPC2 catalog (Williams et al. 1996). The HDFS NICMOS field (Fruchter et al. 1998) was also considered in the survey, together with the VLT Science Verification optical data (Renzini 1998).

The 23 fields are listed in Table 1 together with the exposure times in different bands and the effective area covered. The latter was computed as the intersection of the IR and optical fields of view. We ran extensive simulations ($\geq 10,000$ per field) in order to measure the probability of detection of a compact elliptical-like source as a function of magnitude and to correct...
the raw counts for completeness. At our magnitude limits, the completeness was always higher than 90%.

3. BUILDING THE CATALOG

The pedestal (e.g., Treu et al. 1998) was subtracted from the calibrated data by using dedicated software. The images were otherwise reduced in the standard way. The preliminary $H_{16}$ catalog was obtained by running SExtractor (Bertin & Arnouts 1996) on the co-added images. The detected sources were inspected on the single frames to avoid defects, and the magnitudes were checked against aperture photometry. We considered as resolved all the sources with FWHM as measured with IMEXAMINE greater than the FWHM of the stars on the co-added frames (resolution quality 1). When the signal-to-noise ratio was high enough, the dimensions were checked on the single frames. In fields with no stars, we considered as resolved objects with a FWHM greater than 1.5 pixels (resolution quality 2). When WFPC2 images were available and the objects were detected in optical, we required them to be resolved also in the optical image. Resolution quality 3 was assigned to objects with FWHM similar to the stars or of the order of 1.5 pixels if no stars were present. Resolution quality 4 was assigned to objects more compact than stars or smaller than 1.5 pixels, if no stars were present. Only objects with resolution quality 1 and 2 were considered in the final sample.

Since the main aim of this survey is to provide a morphologically selected sample of HizECs, we limited the $H_{16}$ band catalog to the relatively bright sources. The limiting magnitudes listed in Table 1 were obtained by cutting each luminosity-sorted catalog at the level where all the sources were detected with a MAGERR_BEST SExtractor parameter smaller than 0.15 (and then rounded to the next brightest half magnitude). Unfortunately, the HDFS NICMOS flanking fields have a relatively shallow optical counterpart, and therefore it was pointless for our purposes to go fainter than $H_{16} = 23.5$. The limit $H_{16} = 24.5$ was used for the HDF and the HDFS, where deeper optical images are available.

After cross-identification of the brightest sources, the $H_{16}$ images were aligned with the other passbands and aperture photometry was performed for all the resolved objects. We used large apertures in order to measure total magnitudes. As a double check, SExtractor was run on the optical images. The two photometries were consistent within the errors for all the objects in the final catalog.

The objects not detected in the optical were assigned an upper limit to the luminosity corresponding to the 3 $\sigma$ background fluctuation on a fixed aperture of 0.25 arcsec$^2$ for the HST images and 2 times the FWHM for the Cerro Tololo Inter-American Observatory (CTIO) and NTT images. Since the CTIO images were taken under different seeing conditions, with different pointings and cameras, we did not combine them, but instead we computed the limiting magnitude from the combined probability of nondetection. The combined limiting magnitudes are $I = 25.7$ and $R = 26.45$. When only the images by Teplitz et al. (1998) were available, the 3 $\sigma$ limiting magnitudes were measured to be $I = 25.6$ and $R = 26.05$.

The colors were finally corrected for galactic extinction using the coefficients and the $E(B-V)$ values given by Schlegel et al. (1998). All the resolved objects in the catalog that satisfied the color selection criteria were morphologically classified independently by the authors, dividing them into three morphological bins: E/S0, S, and Ir. Only the objects for which we agreed on the classification were assigned a morphological type.

4. RESULTS AND CONCLUSIONS

The observed integrated surface density of HizECs as a function of magnitude is shown in Figure 1 for the low- (hexagons) and high-redshift (triangles) selection criteria. It is worth stressing that this measurement was performed in random fields, whereas many of the known EROs or high-redshift elliptical galaxies are radio selected or found in the vicinity of QSOs or active galactic nuclei, so that their inferred surface density may be biased.

Figure 1 also shows the predictions of a class of models. These are similar to the ones computed by Zepf (1997) and assume a constant comoving density, passive evolution after a single burst of star formation at $z = z_f$, and a Schechter local luminosity function (LF). The parameters for the local LF were taken from Gardner et al. (1997) scaling the total normalization factor to the fraction of E/S0 (32%; Gardner 1998). The predictions of the models are shown as solid (high-redshift) and dotted (low-redshift) lines for different cosmologies and different redshifts of formation. In each case we scaled the normalization factor in order to match the observed counts. We confirm previous results (Cowie et al. 1994; Zepf 1997; Barger et al. 1999; Kodama, Bower, & Bell 1999; see, however, Bentez et al. 1999) that fewer objects are observed than predicted by a passively evolving model of galaxies formed at very high redshift (5 or 10 depending on cosmology). In addition, the following can be noticed.

1. Models with a very low redshift of formation for the stellar populations of E/S0’s ($z \lesssim 2$, cases a and b in Fig. 1) do not account for the observed population of HizECs, since no object red enough is predicted.

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5 Only in field 1509-1126 the probability goes down to 77% at $H = 23.5$ due to the presence of a bright star.
2. Models in which a significant fraction of the current E/S0 population was already assembled at $z = 1-2$ and the stellar population was formed at higher redshift (5 or 3) describe the observed counts well. The exact fraction of objects depends to some extent on the normalization of the local LF, but the results are qualitatively unchanged if different E/S0 LFs are used. For example, using the parameters from Marzke et al. (1998), about 25% of current E/S0's are needed to fit our data for case e.

3. If we halve the local LF, assuming that only E's form in short bursts of star formation at high redshift, the fraction of progenitors already assembled at high-redshift doubles: the data are consistent with a scenario in which a large fraction of E's form at high redshift and evolve passively, while the S0's form later or undergo late episodes of star formation or interactions. Surface photometry can help address this issue.

4. It is possible to break the degeneracy between redshift of formation and fraction of population by means of two selection criteria sensitive to slightly different redshift intervals. For example, model d can be made to match the broad criterion number counts, but does not predict any object red enough to satisfy the high-redshift criterion. The same qualitative behavior can be noticed in model c even though the errors are still too large to rule out this particular model.

It should be noticed that our measurement of HizECs' number density may be considered as a lower limit on the actual number of objects because (1) very compact, not resolved, E/S0's drop out of the sample since they are not resolved; (2) E/S0's may be rejected by their morphology if, e.g., they are disturbed by a dwarf companion or by an interaction. In addition, single burst models produce the reddest possible colors for a given $z$, cosmology, and metallicity. Therefore also the color selection criteria are tuned to produce a lower limit. Unfortunately, the residual possibility of contamination from regular-looking dusty starbursts prevents us from pushing the lower limit interpretation of our measurement. A spectroscopic follow-up of the brightest candidates is needed to assess the magnitude of this contamination, if at all present.

Taking our result at face value, a large fraction of the zero-redshift E/S0 population is not detected as HizECs at $z \geq 1$. Possible interpretations are that they may have been assembled at lower redshift, may be interacting, or may be bluer than required by our color selection criteria due to a more complicated star formation history with delayed star formation (e.g., Jimenez et al. 1999). We plan to test the prediction of alternate models in Paper II.

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