The Astrophysical Journal, 511:L97–L100, 1999 February 1

THE FORNAX SPECTROSCOPIC SURVEY: THE NUMBER OF UNRESOLVED COMPACT GALAXIES

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Received 1998 August 21; accepted 1998 November 24; published 1998 December 10

ABSTRACT

We describe a sample of 13 bright ($18.5 < B_J < 20.1$), compact galaxies at low redshift ($0.05 < z < 0.21$) behind the Fornax Cluster. These galaxies are unresolved on UK Schmidt sky survey plates, and so they would be missing from most galaxy catalogs compiled from this material. The objects were found during initial observations of *The Fornax Spectroscopic Survey*. This project is using the Two-degree Field spectrograph on the Anglo-Australian Telescope to obtain spectra for a complete sample of *all* 14,000 objects, *stellar and nonstellar*, with $16.5 < B_J < 19.7$, in a 12 deg^2 area centered on the Fornax Cluster of galaxies. The surface density of compact galaxies with magnitudes $16.5 < B_J < 19.7$ is 7 ± 3 deg^{-2}, representing 2.8% ± 1.6% of all local ($z < 0.2$) galaxies to this limit. There are 12 ± 3 deg^{-2} with $16.5 < B_J < 20.2$. They are luminous ($-21.5 < M_B < -18.0$, for $H_0 = 50$ km s^{-1} Mpc^{-1}), and most have strong emission lines (Hα equivalent widths of 40–200 Å) and small sizes typical of luminous H II galaxies and compact narrow emission line galaxies. Four out of 13 have red colors and early-type spectra, and so they are unlikely to have been detected in any previous surveys.

Subject headings: galaxies: compact — galaxies: general — galaxies: starburst

1. INTRODUCTION

Galaxy detection in many optical surveys, especially those based on photographic data, suffers from strong selection effects as a function of surface brightness. The difficulty of detecting low surface brightness galaxies is well accepted (Impey, Bothun, & Malin 1988; Ferguson & McGaugh 1995), but at the other extreme, it has been argued that there is *no* strong selection against high surface brightness galaxies (Allen & Shu 1979; van der Kruit 1987). Most galaxy surveys that are based on photographic material ($B_J < 21$) have assumed—implicitly—that very few, if any, galaxies are unresolved (see, e.g., Maddox et al. 1990b). Morton, Krug, & Tritton (1985) attempted to check this, taking spectra of all 606 stellar objects brighter than $B = 20$ in an area of 0.31 deg^2, but found no galaxies. Colless et al. (1991) found seven galaxies among a sample of 117 faint compact objects, but these were so faint ($B_J \simeq 22.5$) that the image classifications were not conclusive.

Many unresolved galaxies have been found in QSO surveys (Downes & Margon 1981; Koo & Kron 1988; Boyle, Jones, & Shanks 1991). More recently, the Edinburgh-Cape blue object survey (Stobie et al. 1997) and the Anglo-Australian Observatory, Two-degree Field QSO redshift survey (Boyle et al. 1999) have produced further examples. Many compact galaxies have also been found among H II galaxies in objective prism surveys: some 50% of these have starlike morphology (Melnick 1987). The compact narrow emission line galaxies (CNELGs) found in the Koo & Kron (1988) survey have been studied in detail (Koo et al. 1994, 1995; Guzmán et al. 1996, 1998): 35 have been found in an area of 1.2 deg^2 to a magnitude limit of $B_J = 22.5$. These are very blue, with luminosities, scale sizes, and emission-line spectra typical of nearby luminous H II galaxies (cf. Salzer, MacAlpine, & Boroson 1989; Terlevich et al. 1991; Gallego et al. 1997). Similar galaxies have been found at higher ($0.4 < z < 1$) redshifts (Phillips et al. 1997), and their distribution may even extend to $z \approx 3$ (Lowenthal et al. 1997).

In this Letter, we describe a new sample of bright ($B_J \lesssim 20.1$), compact galaxies that are unresolved on the photographic sky survey plates commonly used to create galaxy catalogs. Unlike previous work, this sample is from a complete spectroscopic survey of *all* objects in an area of sky, and so we can estimate the fraction of all galaxies that are compact. A population of compact galaxies that is missing in normal galaxy surveys (see, e.g., Colless 1998) would be important for several reasons (Schade & Ferguson 1994).

2. THE FORNAX SPECTROSCOPIC SURVEY

The Fornax Spectroscopic Survey (see Drinkwater et al. 1998 for details) is designed to provide a census of galaxies in the local universe that is free of morphological selection criteria. We are using the Two-degree Field (2dF) spectrograph on the Anglo-Australian Telescope to obtain spectra for all 14,000 objects, stellar and nonstellar, in four 2dF fields (12.5 deg^2) centered on the Fornax Cluster, with magnitude limits of $16.5 < B_J < 19.7$ (and somewhat deeper for unresolved images). Our targets are drawn from a UK Schmidt B_J sky survey plate that is centered on the Fornax Cluster (Phillipps et al. 1987) and digitized by the Automated Plate Measuring (APM) Facility (Irwin, Maddox, & McMahon 1994). Although we observe objects of all morphological types, we used the automated APM classifications of the objects as "stellar" (probably stars) or "resolved" (probably galaxies) in order to optimize our photographic photometry. The magnitudes of the resolved objects were measured by fitting exponential intensity profiles to the run of area against the isophotal threshold in the APM data (Davies et al. 1988; Davies 1990). The stellar B_J magnitudes

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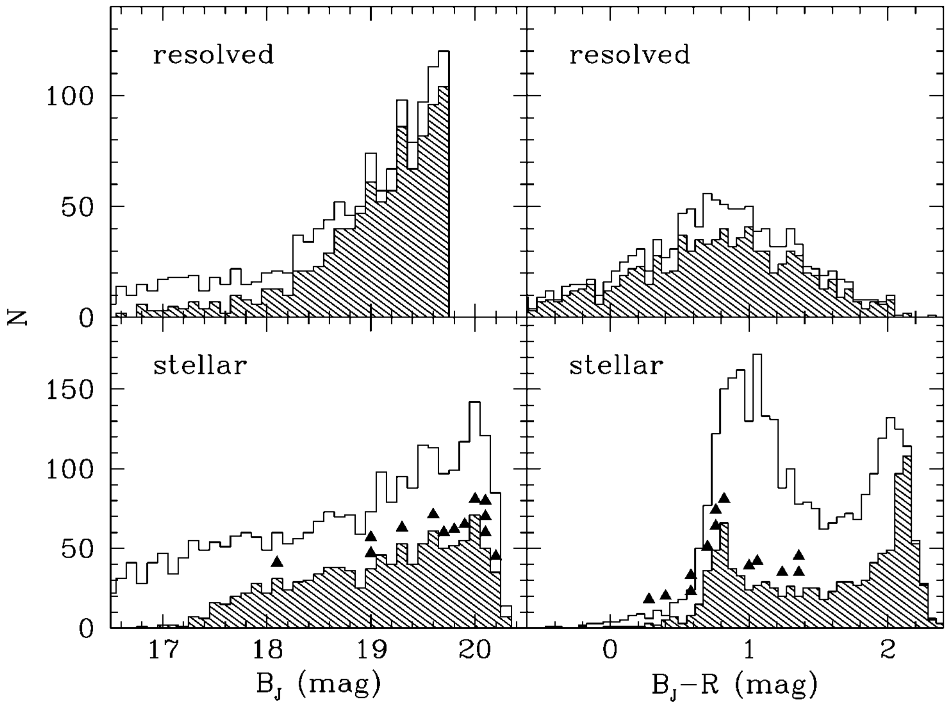

FIG. 1.—Histograms showing the completeness of our observations as functions of magnitude and color for stellar and resolved objects. The colors were taken from the APM catalog using magnitudes derived from stellar profile fitting, and so they are only indicative for the resolved objects. In each case, the upper histogram is the total number of objects, and the lower histogram gives the number observed and identified. The triangles indicate the locations of the new compact galaxies.

were taken from the APM catalog data (Irwin et al. 1994), which uses internal self-calibration to fit stellar profiles, correcting for the nonlinear response of the photographic emulsion.

Here we present preliminary results from the first field centered at $\alpha = 03^h38^m29^s$, $\delta = -35°27'01''$ (J2000) observed in semesters 1996B and 1997B. We observed and identified 992 (77%) of the resolved objects to a limit of $B_J < 19.7$, 675 (38%) of stellar objects to the same limit and a total of 1112 (43%) of the stellar objects to the deeper limit of $B_J < 20.2$. Figure 1 shows the completeness of our observations as a function of magnitude and color. Our main result is that 13 of the "stellar" objects have recession velocities of 14,000–60,000 km s^{-1} (see Table 1). These galaxies are well beyond the Fornax Cluster ($v \simeq 1500$ km s^{-1}), and most (nine) have strong emission-line spectra.

3. PROPERTIES OF THE NEW GALAXIES

In Figure 2, we compare the distribution of the new compact galaxies with previously detected CNELGs (Koo et al. 1994, 1995) in magnitude-redshift space. There is considerable overlap in absolute magnitude, but, as expected from a larger area survey with a brighter magnitude limit, our galaxies occupy a region in this diagram at lower redshift and brighter apparent magnitude.

The compact nature of the new galaxies prohibits a detailed

TABLE 1
PROPERTIES OF THE COMPACT GALAXIES

R.A. (J2000)	Decl. (J2000)	z	V (mag)	$B-V$ (mag)	$V-I$ (mag)	B_J (mag)	$B-V_0$[a] (mag)	M_B[a] (mag)	[O III]/Hβ	[N II]/Hα	$W_{H\alpha}$ (Å)
3 34 45.47	−35 38 18.0	0.0453	18.73 ± 0.08	0.52 ± 0.10	0.48 ± 0.14	19.1	0.43	−18.0	4.0	0.12	39
3 34 53.03	−36 03 03.5	0.2130	19.20 ± 0.08	1.00 ± 0.16	0.83 ± 0.15	19.9	0.57	−21.1	2.5	0.21	40
3 35 33.06	−35 01 12.8	0.1593	18.12 ± 0.05	0.55 ± 0.06	0.90 ± 0.07	18.5	0.55	−21.5	1.8	0.25	133
3 38 56.50	−35 45 00.3	0.1157	19.42 ± 0.09	0.22 ± 0.12	0.71 ± 0.16	19.6	0.22	−19.8	4.6	0.12	189
3 39 18.37	−35 32 40.7	0.1838	18.40 ± 0.04	0.93 ± 0.10	1.27 ± 0.05	19.1	0.55	−21.5	…	0.42	6
3 39 51.33	−35 47 52.8	0.1553	19.09 ± 0.06	0.86 ± 0.14	1.23 ± 0.08	19.7	0.55	−20.4	…	…	…
3 40 06.66	−36 04 27.1	0.1156	18.79 ± 0.05	0.74 ± 0.09	0.80 ± 0.09	19.3	0.51	−20.6	…	0.39	59
3 40 25.54	−34 58 33.5	0.1039	19.11 ± 0.07	0.47 ± 0.12	0.90 ± 0.15	19.4	0.47	−19.6	…	…	8
3 40 57.25	−35 10 34.1	0.1616	19.08 ± 0.06	1.30 ± 0.20	1.00 ± 0.10	20.0	0.84	−20.4	…	…	…
3 41 32.89	−35 20 08.4	0.0778	19.73 ± 0.18	0.50 ± 0.20	0.65 ± 0.28	20.1	0.34	−18.3	3.29	0.13	44
3 41 56.94	−35 44 01.0	0.1163	19.71 ± 0.12	0.61 ± 0.21	0.82 ± 0.20	20.1	0.39	−19.2	4.01	0.11	31
3 41 59.59	−35 09 01.2	0.1391	18.84 ± 0.06	0.80 ± 0.11	1.05 ± 0.09	19.4	0.53	−21.0	1.72	0.34	136
3 42 38.68	−35 56 21.9	0.1070	19.42 ± 0.09	0.58 ± 0.14	0.92 ± 0.12	19.8	0.37	−19.3	3.10	0.21	138

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] K-corrected (Coleman, Wu, & Weedman 1980) using $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$.

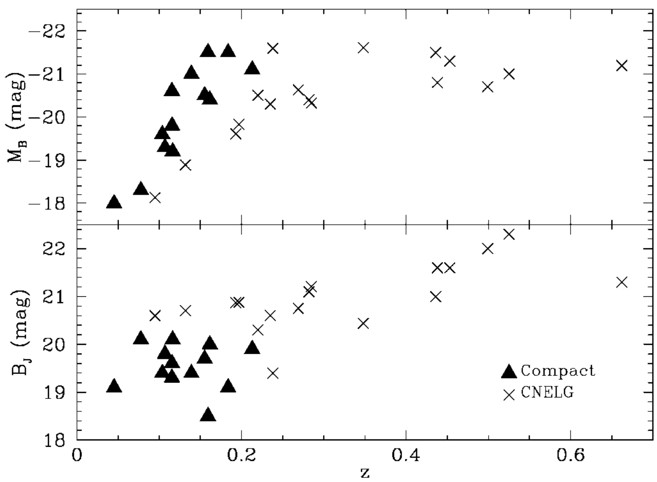

FIG. 2.—Distribution of absolute and apparent magnitudes of the new compact galaxies (*triangles*) compared with the Koo et al. (1994, 1995) CNELGs (*crosses*) as a function of redshift.

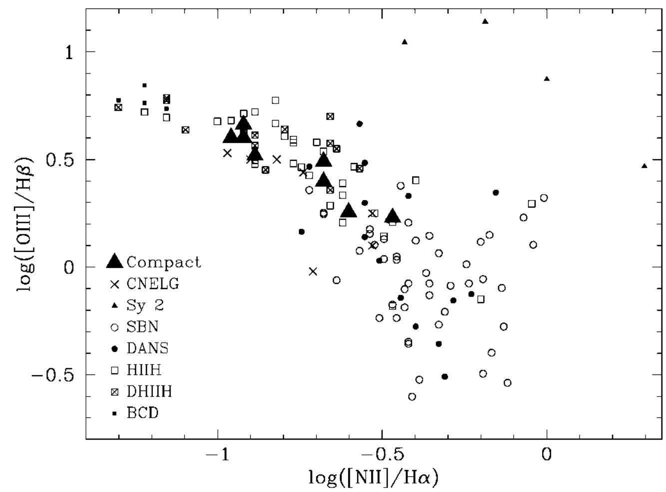

FIG. 3.—Emission-line diagnostic diagram of [O III]/Hβ vs. [N II]/Hα. The new compact galaxies (*triangles*) are compared with CNELGs (*crosses*) and a range of local galaxies from the UCM survey (Gallego et al. 1997).

analysis of their scale sizes and central surface brightness using our imaging data. The galaxy images are unresolved on photographic sky survey plates (1$''\!.$5 seeing FWHM). We therefore estimate conservative upper limits (not correcting for photographic saturation, which occurs at about 21 B mag arcsec^{-2}) to their scale lengths to be $\simeq 1''$ (assuming an image FWHM of 1$''\!.$5). This upper limit has been confirmed by a CCD image of one of the galaxies taken with the Cerro Tololo Inter-American Observatory[8] 1.5 m Telescope, which was only marginally resolved in 1$''\!.$2 seeing. At the range of distances indicated, this corresponds to physical scale sizes of 1–4 kpc,[9] which are somewhat smaller than local spiral galaxies (de Jong 1996) and at least as small as CNELGs and luminous H II galaxies (Phillips et al. 1997). Despite the small scales, these galaxies are not dwarfs in terms of their luminosities, which are within a factor 10 or so of L_*; indeed, some of them exceed L_*. This is true for the following reason: their high surface brightnesses; the scale size limits of 1$''$ imply central surface brightnesses 19–21 B mag arcsec^{-2}, as bright as the CNELGs and the luminous H II galaxies (Phillips et al. 1997).

We obtained Cousins *BVI* CCD images of our survey region using the CTIO Curtis Schmidt Telescope. The low spatial resolution (3$''$ FWHM) leaves the compact galaxies unresolved, but the data allow us to calculate the photometry and aperture (8$''$ radius) colors. The K-corrected $B - V$ colors (Table 1) of the emission-line compact galaxies place them among the CNELG and H II galaxies, and they are consistent with the relatively high, recent star formation rates (Larson & Tinsley 1978).

The nine emission-line compact galaxies all have strong narrow Hα lines: none are resolved at our resolution of 9 Å or 450 km s^{-1}. The Hα rest equivalent widths listed in Table 1 nearly all exceed the mean value for our overall background sample of emission-line objects of EW(Hα) $\simeq$ 37 Å, which is typical of local spirals (Kennicutt 1992). The values for the compact galaxies, ~30–190 Å, are more like those seen in low-redshift H II galaxies (Gallego et al. 1997). Given the range of overall sizes of these objects, it is interesting to consider what Cowie et al. (1996) call the stellar mass doubling time, i.e., the time it would take for the current star formation rate (SFR) to double the existing underlying stellar mass. This can be derived directly from the equivalent widths: Cowie et al. note that EW(Hα) $\simeq$ 60 Å separates galaxies undergoing rapid star formation, with mass doubling times less than 10^{10} yr, from those with moderate SFRs that can be maintained for a Hubble time. At the highest SFR, Cowie et al. find that a mass doubling time of 2×10^9 yr corresponds empirically to their galaxies with EW(Hα) $\simeq$ 125 Å. Our fastest star formers, like J0338$-$3545, should have mass doubling times of this order.

In Figure 3, we show the [O III]/Hβ versus [N II]/Hα emission-line ratio diagram for our new galaxies compared with the Gallego et al. (1997) emission-line sample and the Koo et al. CNELGs. This shows that new compact galaxies are actively star-forming as they closely follow the general H II region relationship. They display generally high excitation as measured by [O III]/Hβ, putting them in the H II galaxies with hot spots (HIIH) class more than the starburst nucleus class as defined by Gallego et al. The new compact galaxies have very similar properties to the CNELGs. We do not draw any conclusion from the lack of low-excitation objects: this may be a selection effect, since we are only considering the unresolved galaxies in our survey in this sample. Similar conclusions can be drawn from a plot of the excitation against absolute magnitude.

We also found four compact galaxies that did not have strong emission lines and therefore are not shown in the excitation diagrams. These are unlikely to have been detected in previous work on compact galaxies because of their weak line emission and generally redder colors, which would exclude them from most QSO surveys. One of them, J0339$-$3547, has a poststarburst spectrum with strong Balmer absorption lines. We have used the two ratios of absorption feature strengths Ca II H + Hϵ/Ca II K and Hδ/Fe I λ4045 to estimate the age of the galaxy since the end of the starburst (Leonardi & Rose 1996). For J0339$-$3547, these ratios are 0.89 and 0.69, respectively. For the Leonardi & Rose model of a starburst lasting 0.3 Gyr, this is indicative of a very strong starburst about 1 Gyr after the end of the burst. This galaxy may represent an intermediate

[8] CTIO is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation as part of the National Optical Astronomy Observatories.

[9] We adopt $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$.

stage between the CNELG types and the dwarf spheroidal remnants proposed by Koo et al. (1995). By comparison, J0340−3510 has ratios of 1.12 and 0.97, and a composite spectrum of 60 normal, early-type galaxies from the survey has values of 1.10 and 0.95, both consistent with the Leonardi & Rose values for an old population.

4. NUMBERS OF COMPACT GALAXIES

To estimate the true numbers of compact galaxies from our sample, we must first make a completeness correction. The color distributions in Figure 1 show that the compact galaxies are all bluer than $B_J - R_F = 1.6$, so the best correction can be taken from the fraction of blue ($B_J - R_F < 1.6$) stellar objects observed; to $B_J = 19.7$, we observed 31% of the blue stellar objects, so the corrected number of compact galaxies to this limit is $7/0.31 = 23 \pm 9$, which is equivalent to a surface density of 7 ± 3 deg^{-2}. The surface density to $B_J = 20.2$ (completeness of 35%) is 12 ± 3 deg^{-2}.

We can use our observations of field galaxies to estimate the fraction of normal galaxies represented by the compact galaxies. At redshifts $z > 0.2$, the Hα line is shifted out of our 2dF spectra, and our galaxy sample is less complete, so we define a "local" comparison field sample to be all galaxies in the field beyond the Fornax Cluster but at redshifts $z < 0.2$. We successfully observed 992 resolved objects to $B_J = 19.7$, of which 675 were "local" background galaxies: this is the minimum number of local field galaxies. There are $1296 - 992 = 304$ resolved objects still to observe, so the maximum number of local field galaxies is $675 + 304 = 979$. The number of local ($z < 0.2$) background galaxies to our limit is 827 ± 152. Therefore, the expected 23 compact galaxies among the stellar objects constitute $2.8\% \pm 1.6\%$ of the local galaxy population. These would be missed by any surveys of objects classified by the APM as "galaxies" from UK Schmidt photographic data with $16.5 < B_J < 19.7$. These selection criteria are typical of previous surveys (Maddox, Efstathiou, & Sutherland 1990a; Colless 1998).

This conclusion is for a magnitude, not volume, limited sample, but in fact the compact galaxies do occupy a similar volume of space to the general run of galaxies to this magnitude limit. For instance, the 2dF galaxy redshift survey, limited at a very similar B_J to ours, has a mean redshift of 33,000 km s^{-1} (Colless 1998), which is close to the mean of the compact galaxies. The galaxy catalog used for that survey has a mean surface density of 222 deg^{-2} at $B_J < 19.7$ (M. Colless 1998, private communication), for which the compact galaxies would represent an additional $3.2\% \pm 1.2\%$.

Only about half of the local galaxy sample exhibits significant emission-line features, so the new compact galaxies constitute a larger fraction of emission-line galaxies (3%–5%). They contribute an even larger fraction of strong Hα emitters with EW(Hα) > 40 Å, and so they may make a small but measurable contribution to the local star formation rate.

The new compact galaxies have very similar absolute magnitudes, sizes, and (in most cases) emission-line properties to the Koo et al. (1994, 1995) CNELGs. The distributions shown in Figure 2 suggest that they are a continuation of the CNELGs to lower redshifts and brighter apparent magnitudes. A better way to compare these populations is by the volume density. Koo et al. (1994) derive a CNELG density of 7.5×10^{-5} Mpc^{-3} compared with the value of 17×10^{-5} Mpc^{-3} for local HIIH + dwarf HIIH galaxies (Salzer et al. 1989). For our sample of compact galaxies, using the $1/V_{max}$ method, we obtain a similar value of $(13 \pm 4) \times 10^{-5}$ Mpc^{-3}. These results are consistent with the respective galaxy populations being related, but we prefer not to draw any conclusions until we can analyze the compact galaxies in the context of our complete sample.

We thank our referee for detailed suggestions that greatly improved the presentation of this work. We also thank Lewis Jones for helpful discussions and Jesus Gallego for providing data for Figure 3. S. P. acknowledges the support of the Royal Society via a University Research Fellowship. J. B. J. is supported by the UK PPARC. Part of this work was done at the Institute of Geophysics and Planetary Physics, under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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