THE FORNAX SPECTROSCOPIC SURVEY: THE NUMBER OF UNRESOLVED COMPACT GALAXIES

Michael J. Drinkwater1,7, Steven Phillipps2, Michael D. Gregg3, Quentin A. Parker4, Rodney M. Smith5, Jonathan I. Davies6, J. Bryn Jones2, Elaine M. Sadler6

Accepted 1998 November for Astrophysical Journal Letters

ABSTRACT

We describe a sample of thirteen 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, so 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 14000 objects, stellar and non-stellar, with 16.5 < B_J < 19.7, in a 12 square degree area centered on the Fornax cluster of galaxies. The surface density of compact galaxies with magnitudes 16.5 < B_J < 19.7 is 7 ± 3deg⁻², representing 2.8 ± 1.6% of all local (z < 0.2) galaxies to this limit. There are 12 ± 3deg⁻² with 16.5 < B_J < 20.2. They are luminous (−21.5 < M_B < −18.0, for H₀ = 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 thirteen have red colors and early-type spectra, so 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 strong selection effects as a function of surface brightness. The difficulty of detecting low surface brightness galaxies is well accepted (Impey, Barth & 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 1975; van der Kruit 1987). Most galaxy surveys based on photographic material (B_J < 21) have assumed—implicitly—that very few, if any, galaxies are unresolved (e.g. Maddox et al. 1990). Morton, Krug & Tritton (1985) attempted to check this, taking spectra of all 606 stellar objects brighter than B = 20 in an area of 0.31deg² 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 ≈ 22.5) that the image classifications were not conclusive.

Many unresolved galaxies have been found in QSO surveys (Downes & Marcon, 1981; Koo & Kron 1988; Boyle et al. 1991). More recently the Edinburgh-Cape blue objective survey (Stobie et al. 1997) and the Anglo-Australian Observatory 2dF QSO redshift survey (Boyle et al. 1998) 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; Koo et al. 1995). Guzmán et al. (1990). Guzmán et al. (1998): 35 have been found in an area of 1.2deg² 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 et al. 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 ≈ 3 (Lowenthal et al. 1997).

In this Letter we describe a new sample of bright (B_J ≤ 20.1), compact galaxies 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, so we can estimate the fraction of all galaxies which are compact. A population of compact galaxies missing in normal galaxy surveys (e.g. Colless 1998) would be important for several reasons (Scheide & 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 free of morphological selection criteria. We are using the Two-degree Field spectrograph (2dF) on the Anglo-Australian Telescope to obtain spectra for all 14,000 objects, stellar and non-stellar, in four 2dF fields (12.5deg²) 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

1School of Physics, University of New South Wales, Sydney 2052, Australia
2Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK
3University of California, Davis, and IGPP, Lawrence Livermore National Laboratory, L-413, Livermore, CA 94550, USA
4Anglo-Australian Observatory, Coonabarabran, New South Wales, 2357, Australia
5Department of Physics and Astronomy, University of Wales Cardiff, PO Box 913, Cardiff CF2 3YB, UK
6School of Physics, University of Sydney, New South Wales 2006, Australia
7Visiting Astronomer, Cerro Tololo InterAmerican Observatory, National Optical Astronomy Observatory

arXiv:astro-ph/9812028v1 1 Dec 1998

Preprint typeset using LATEX style emulateapj
a UK Schmidt $B_t$ sky survey plate centered on the For-
man Cluster \cite{Phillips1987} digitized by the Au-
mented Plate Measuring facility (APM) \cite{Irwin1994}. Although we observe objects of all
morphological types, we used the automated APM clas-
sifications of the objects as “stellar” (probably stars) or “re-
solved” (probably galaxies) to optimize our photographic
photometry. The magnitudes of the resolved objects were mea-
sured by fitting exponential intensity profiles to the
run of area against isophotal threshold in the APM data \cite{Davies1988, Davies1990}. The stellar $B_t$
magnitudes were taken from the APM catalog data \cite{Irwin1994} which uses internal self-calibration
to fit stellar profiles, correcting for the non-linear response of the photographic emulsion.

Here we present preliminary results from the first field
centered at $\alpha = 03^h38^m29^s, \delta = -35^\circ27'01''$ ($J2000$) ob-
served 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
deepener limit of $B_J < 20.2$. Figure 3 shows the complete-
ess of our observations as a function of magnitude and
color. Our main result is that thirteenth 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 ($v \approx 1500$ 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 com-
pact galaxies to previously detected CNELGs \cite{Koo1994, Koo1995} in magnitude-redshift space. There
is considerer overlap in absolute magnitude, but as ex-
pected 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 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
$\approx 1''$ (assuming an image FWHM of 1$''$5). This upper
limit has been confirmed by a CCD image of one of the
galaxies taken with the CTIO 8.5m Telescope which was
only marginally resolved in 1$''$2 seeing. At the range of dis-
tances indicated, this corresponds to physical scale sizes of
1–4 kpc, somewhat smaller than local spiral galaxies \cite{Jong1996}, and at least as small as CNELGs and lumi-
nous HII galaxies \cite{Phillips1997}. Despite the small
scale sizes, these galaxies are not dwarfs in terms of their lu-
nosities which are within a factor 10 or so of $L_\odot$; indeed
some of them exceed $L_\odot$. This is because of their high
surface brightnesses: the scale size limits of 1$''$ imply cen-
tral surface brightnesses $19-21$ mag arcsec$^{-2}$, as bright as the CNELGs and the luminous HII galaxies \cite{Phillips1997}.

We obtained Cousins BVI CCD images of our survey re-
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 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 HII galaxies, and are consis-
tent with relatively high recent star formation rates \cite{Lar-
son1978}.

The nine emission-line compact galaxies all have strong
narrow H$\alpha$ lines; none are resolved at our resolution of 9 A
or 450 km s$^{-1}$. The H$\alpha$ rest equivalent widths listed in Ta-
ble 1 nearly all exceed the mean value for our overall back-
ground sample of emission line objects of $EW(H\alpha) \approx 37\,\text{A}$, typical of local spirals \cite{Kennicutt1993}. The values for the compact galaxies, $\approx 30-190\,\text{A}$ are more like those seen in
low redshift HII galaxies \cite{Gallego1997}. 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 under-
lying stellar mass. This can be derived directly from the
equivalent widths: Cowie et al. note that
$EW(H\alpha) \approx 60\,\text{A}$
separates galaxies undergoing rapid star formation, with
mass doubling times less than $10^{10}$ years, from those with
moderate SFRs which can be maintained for a Hubble
time. At the highest SFR, Cowie et al. find that a mass
doubling time of $2 \times 10^{9}$ years empirically corresponds to
their galaxies with $EW(H\alpha) \approx 125\,\text{A}$. Our fastest star
formers, like J0338–3545, should have mass doubling times of
this order.

In Figure 3 we show the [OII]/H$\beta$ vs. [NII]/H$\alpha$
emission line ratio diagram for our new galaxies compared to 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 HII
region relationship. They display generally high excitation as
measured by [OII]/H$\beta$, putting them in the HII class
more than the starburst nucleus class as defined by Gal-
lego et al. The new compact galaxies have very similar
properties to the CNELGs. We do not draw any conclu-
sion from the lack of low excitation objects: this may be a
selection effect as 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 which did not have
strong emission lines and are therefore not shown in the
excitation diagrams. These are unlikely to have been de-
lected 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 post starburst spectrum with
strong Balmer absorption lines. We have used the two
ratios of absorption feature strengths CaIIH+He/CaIIK
and H$\beta$/FeI4045 to estimate the age of the galaxy since
the end of the starburst \cite{Leonardi1990}. For
J0339–3547 these ratios are 0.89 and 0.69 respectively.
For the Leonardi & Rose model of a starburst lasting

---

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

9We adopt $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.1$. 
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 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 2 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 $7 \pm 0.31 = 23 \pm 9$, equivalent to a surface density of $7 \pm 3 \text{deg}^{-2}$. The surface density to $B_J = 20.2$ (completeness of 35%) is $12 \pm 3 \text{deg}^{-2}$.

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 Ho 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 $827 \pm 152$. The expected 23 compact galaxies among the stellar objects therefore 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 et al. 1990, 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 33000 km s$^{-1}$ (Colless 1998), 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, 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 $EW(\text{H}\alpha) > 40$ Å, so 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 $7.5 \times 10^{-3} \text{Mpc}^{-3}$ compared to the value of $17 \times 10^{-3} \text{Mpc}^{-3}$ for local HII plus DHIH galaxies (Salzer et al. 1989). For our sample of compact galaxies, using the $1/V_{\text{max}}$ method we obtain a similar value of $(13 \pm 4) \times 10^{-5} \text{Mpc}^{-3}$. 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 which greatly improved the presentation of this work. We also thank Dr. Lewis Jones for helpful discussions and Dr. Jesus Gallego for providing data for Figure 3. SP acknowledges the support of the Royal Society via a University Research Fellowship. JBJS 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 U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

REFERENCES

Allen, R. J., Shu, F. H. 1979, ApJ, 227, 67
Boyle, B.J., Jones, L.R., Shanks, T. 1991, MNRAS, 251, 482
Boyle, B.J., Smith, R.J., Shanks, T., Croom, S.M., Miller, L., Read, M. 1998, in IAU Symp. 183, Cosmological Parameters and Evolution of the Universe, in press
Colless, M., van den Bosch, G., Weedman, D.W. 1980, ApJS, 43, 393
Colless, M. 1998, Phil.Trans.R.Soc.Lond.A, in press
Colless, M., Ellis, R.S., Taylor, K., Shaw, G. 1991, MNRAS, 253, 868
Cowie, L.L., Songaila, A., Hu, E.M., Cohen, J.G. 1996, AJ, 112, 839
Davies, J.J. 1990, MNRAS, 245, 350
Davies, J.J., Phillipps, S., Capron, M.G.M., Disney, M.J., Kibblewhite, E.J. 1988, MNRAS, 232, 239
Downes, R.A., Marcon, B. 1981, AJ, 86, 19
Drinkwater, M.J., Phillipps, S., Davies, J.J., Gregg, M.D., Jones, J.B., Parker, Q.A., Sadler, E.M., Smith, R.M. 1998, MNRAS, in preparation
Ferguson, H.C., McGaugh, S.S. 1995, AJ, 440, 470
Gallego, J., Zamorano, J., Rego, M., Vitores, A.G. 1997 ApJ, 475, 502
Guzmán, R., Koo, D.C., Faber, S.M., Illingworth, G.D., Takamiya, M., Kron, R.G., Bershady, M.A. 1996, ApJ, 460, L9
Guzmán, R., Jangren, A., Koo, D.C., Bershady, M.A., Simard, L. 1998, ApJ, 495, L13
Impey, C., Bothun, G., Malin, D. 1988, ApJ, 330, 634
Irwin, M., Maddox, S., McMahon, R. 1994, Spectrum, 2, 14
de Jong, R.S. 1996, A&A, 313, 45
Kennicutt, R.C. 1992, ApJ Suppl., 79, 255
Koo, D.C., Kron, R.G. 1988, ApJ, 325, 92
Koo, D.C., Bershady, M.A., Wirth, G.D., Stanford, S.A., Majewski, S.R. 1994, ApJ, 427, L9
Koo, D.C., Guzmán, R., Faber, S.M., Illingworth, G.D., Bershady, M.A., Kron, R.G., Takamiya, M. 1995, ApJ, 440, L49
van der Kraut, P.C. 1987, A&A, 173, 59
Larson, R.B., Tinsley, B.M. 1978, ApJ, 219, 46
Leonardi, A.J., Rose, J.A. 1996, AJ, 111, 182
Lowenthal, J.D., Koo, D.C., Guzmán, R., Gallego, J., Phillipps, A.C., Faber, S.M., Vogt, N.P., Illingworth, G.D., Gronwall, C. 1997, ApJ, 489, 543
Maddox, S.J., Sutherland, W.J., Efstathiou, G., Loveday, J. 1990a, MNRAS, 243, 692
Maddox, S.J., Efstathiou, G., Sutherland, W.J. 1990b, MNRAS, 243, 692
Melnick, J. 1987, in Starbursts and Galaxy Evolution, ed. T.X. van den Bergh (Paris: Editions Frontières), 215
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, so are only indicative for the resolved objects. In each case the upper histogram is the total number of objects and the lower gives the number observed and identified. The triangles indicate the locations of the new compact galaxies.

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

Fig. 3.— Emission-line diagnostic diagram of \([\text{OIII}]/\text{H}\beta\) vs. \([\text{NI}]/\text{H}\alpha\). The new compact galaxies (triangles) are compared with CNELGs (crosses) and a range of local galaxies from the UCM survey (Gallego et al. 1997).

### Table 1

**Properties of the Compact Galaxies**

| RA (J2000) | Dec    | $z$  | $V$  | $B-V$ | $V-I$ | $B_J$ | $B-V_0$* | $M_B$* | \([\text{OIII}]\)/$H\beta$ | \([\text{NI}]\)/$H\alpha$ | $W_{H\alpha}$ |
|------------|--------|------|------|-------|-------|-------|----------|-------|----------------|-----------------|-------------|
| 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 | 0.1553 | 19.09±0.06 | 0.86±0.14 | 1.23±0.08 | 19.7 | 0.55 | -20.4 | ... | ... | 42 |
| 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 |
| 3:42:36.68 | -35:56:21.9 | 0.1670 | 19.42±0.09 | 0.58±0.14 | 0.92±0.12 | 19.8 | 0.37 | -19.3 | 3.10 | 0.21 | 138 |

*K-corrected using $H_0 = 50\ \text{km\ s}^{-1}\ \text{Mpc}^{-1}$ and $q_0 = 0.1$.**
