Correlations among the properties of galaxies found in a blind H I survey, which also have SDSS optical data

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ABSTRACT
We have used the Parkes Multibeam system and the Sloan Digital Sky Survey to assemble a sample of 195 galaxies selected originally from their H I signature to avoid biases against unevolved or low surface brightness objects. For each source nine intrinsic properties are measured homogeneously, as well as inclination and an optical spectrum. The sample, which should be almost entirely free of either misidentification or confusion, includes a wide diversity of galaxies ranging from inchoate, low surface brightness dwarfs to giant spirals. Despite this diversity there are five clear correlations among their properties. They include a common dynamical mass-to-light ratio within their optical radii, a correlation between surface brightness and luminosity and a common H I surface density. Such correlation should provide strong constrains on models of galaxy formation and evolution.

Key words: galaxies: evolution – galaxies: fundamental parameters – galaxies: general – galaxies: peculiar – galaxies: structure.

1 INTRODUCTION
Searching for systematic correlations among the global properties of galaxies, analogous to the H-R diagram for stars, may offer the best hope of having a better understanding about their formation and evolution. The recent availability of large and systematic data sets at several wavelengths makes this a good time to search. Such searches go back to the optical pioneers of galaxy exploration such as Hubble (1937), Zwicky (1942), Holmberg (1965) and de Vaucouleurs et al. (1991). The trends and correlations they discovered, re-emerge very clearly in the Sloan Digital Sky Survey (SDSS), as described by Blanton et al. (2003) in their analysis of 200 000 galaxies at redshifts of ∼0.1.

This paper deals with a much smaller sample of galaxies, but ones found by an entirely different technique, i.e. in a blind search for neutral hydrogen gas at 21 cm. The principal motivations for such a blind search are two. First of all, by definition, optically selected galaxies already contain many stars, which may not be the case in the younger, or less evolved galaxies, which may have the most to tell us about their formation and evolution. Apart from X-ray searches, which detect the very hot gas in the potential wells of giant ellipticals, most galaxy searches rely, either directly or indirectly, on the presence of stars and so are biased against young or unevolved objects. Secondly, a blind H I search offers a unique way round the strong optical surface brightness (SB) selection effects, which could disguise the very correlations one is looking for. By definition a galaxy must be separately both luminous enough and large enough to distinguish it above a sky background which, by galaxy standards, is quite bright. These two separate requirements squeeze optically selected galaxies into an extremely narrow range of SBs centred, for a given catalogue, on \( \Sigma_{\text{cut}} \) where

\[
\Sigma_{\text{cut}} = \frac{l_{\text{ap}}}{\pi \theta_{\text{ap}}^2},
\]

where \( l_{\text{ap}} \) and \( \theta_{\text{ap}} \) are the minimum apparent luminosity, and the minimum apparent angular radius which the galaxy catalogue will accept (Disney 1999). The full width at half-maximum (FWHM) of the detectable range is typically only 3 mag wide. Such a narrow stricture certainly impoverished the old photographic surveys (Disney 1976; Disney & Phillipps 1983; Dalcanton et al. 1997). It might be naively thought that CCDs would have cured this stricture. Not so, because they detect galaxies that are both fainter and smaller than emulsions, their \( \Sigma_{\text{cut}} \)'s are (see equation 1) scarcely any dimmer. On the other hand, the limitation with an H I-selected sample is that it will miss the early-type galaxies – which contain very little neutral gas. According to the SDSS survey late types make up the large

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majority of all galaxies, although they may emit less than their fair share of light (Blanton et al. 2001).

Blind H\textsc{i} surveys face four main problems. To reach sources of a given column density of H\textsc{i} ($N_{\text{HI}}$, in atom cm\textsuperscript{-2}) any survey must be at least sensitive enough to find them in the most favourable case, i.e. when they fill the beam. In that case (Minchin et al. 2003; Disney 2008) $t_{\text{de}}$ (per beam) $\geq k/[N_{\text{HI}}(\text{min})]^2$ where $k$ is independent of dish-diameter $D$ (because a larger dish projects the same system size on to a smaller area of sky). Mathematically

$$N_{\text{HI}} \cong 10^{19.1} \left( \frac{M_{\text{HI}}}{L_B} \right) \left( \frac{10^{0.427-P_{\text{HI}}}}{0.1} \right) \text{atom} \text{cm}^{-2} \tag{2}$$

(Disney & Banks 1997), where ($M_{\text{HI}}/L_B$) is in solar units and $P_{\text{HI}}$ is the average SB in B mag arcsec\textsuperscript{-2}, taken over the same area as $N_{\text{HI}}$. Since the effective SB ($\mu_{\text{eff}}$) of an exponential disc is 2.1 mag brighter than $P_{\text{HI}}$ (Salpeter & Hoffman 1996) and as there is a loose correspondence between $N_{\text{HI}}$ and SB (e.g. Swaters et al. 2003) column density sensitivity at the $N_{\text{HI}} < 10^{19.5}$ cm\textsuperscript{-2} level is needed to detect low surface brightness galaxies (LSBGs; i.e. $\mu_{\text{eff}} > 25.0$ B mag arcsec\textsuperscript{-2}) with ($M_{\text{HI}}/L_B$) $\approx 0.3$ (see Section 3), which in turn requires integration times per beam of several hundred seconds – which rendered earlier blind H\textsc{i} surveys either too insensitive or too impractical to detect LSBGs. Since this difficulty was not recognized until recently, some earlier claims, based on small blind H\textsc{i} surveys, to set rigid upper limits to the amount of cosmic H\textsc{i} or the numbers of LSBGs in the Universe, must be set aside (e.g. Shostak 1977; Fisher & Tully 1981; Zwaan et al. 1997).

The coming of the multibeam H\textsc{i} detector (Staveley-Smith et al. 1996) was essential to carry out such blind H\textsc{i} surveys. The H\textsc{i} Parkes All Sky Survey (HIPASS; Meyer et al. 2004) used the first multibeam system to survey the entire Southern sky, and the north up to $+25^\circ$. More than 4000 sources were identified in the Southern sky alone. The Equatorial Survey (ES), described in this paper, was initially part of HIPASS, but with an accelerated search so as to exploit the SDSS Data Release 2 (SDSS-DR2) optical data when it emerged. HIPASS sources are typically more than a degree apart which makes for a real challenge in obtaining complementary optical, and other data, simply because, before SDSS, each source required a separate observing campaign.

The strong clustering of galaxies, and of H\textsc{i} galaxies in particular, makes the identification of the source with an optical candidate quite challenging. This is true even when both 21 cm and optical velocities are known, for galaxy velocities are strongly clustered too. To be certain that every Parkes-detected source was correctly identified with its optical counterpart would require interferometric follow-up in every case – which is infeasible when one is dealing with hundreds of sources, as here. We have used interferometry, coupled with simulations, to be certain that only a handful of the remaining sources (less than 10) are still misidentified. This handful is too small to affect the main correlations.

The ES, reported on here, was a search through HIPASS cubes between declinations $-6^\circ$ and $+10^\circ$. Thus $5780\text{deg}^2$ of H\textsc{i} data, in the velocity range between $-1280$ and $+12700\text{km s}^{-1}$, were searched largely by eye to come up with 1107 sources (Garcia-Appadoo 2005). The Equatorial Strip was chosen because (i) it was approximately perpendicular to the Galactic plane and so it is mostly dark enough to make LSBGs detectable; (ii) it is accessible for follow up with a large range of instruments including the Very Large Array (VLA), and for some of its area the SDSS-DR2; (iii) it includes the area searched for LSBGs by Impey et al. (1996) using the Automated Plate Measurement (APM) machine (Cawson et al. 1987) to scan United Kingdom Schmidt plates. This should eventually lead to an estimate of the number of LSBGs still missing from wide-scale optical surveys. So long as LSBGs remain a putative reservoir for missing baryons (e.g. Fukugita, Hogan & Peebles 1998) it is important to know this. Of the ES area, 50 per cent will eventually be scanned by SDSS, and 35 per cent of it is already publicly released. We concentrated our search in the 1700 deg\textsuperscript{2} of the ES released earlier in DR2 (Abazajian et al. 2004). 370 cross-identifications were made, and then refined down to only 195 to reduce possible misidentifications to a minimum. These 195 sources have SDSS-DR2 optical diameters (50 and 90 per cent light diameter) between 0.16 and 6 arcmin (West et al. 2009). The SDSS pipeline photometry on sources of this size was known to be extremely unreliable so we had to devise new techniques to reduce the data (West 2005), which delayed the project by nearly 2 yr. Eventually we will analyse many more ES sources already observed with SDSS. However, the results found for the first 195 are clear and interesting enough to merit being published now.

We have measured, at 21 cm, the peak flux, the integrated flux, the linewidth and the spectral shape (e.g. two horned or Gaussian mainly), and in the optical the luminosities at u, g, r, i, z, two radii $R_{90}(g)$ and $R_{90}(g)$ containing, respectively, 50 and 90 per cent of the g-band light, the inclination, the morphology and a fibre nuclear spectrum set either on the nucleus or the brightest H\textsc{i} region. Given the strong correlations between some of the colours this amounts to about a dozen independent measurements. Chiefly missing is a rotation curve to spell out the distribution of dark matter. Nevertheless, we have sufficient information to hope that some important aspects of galaxy systematics will emerge. With 13 properties there will be $(13 \times 12)/2 \approx 80$ possible correlations to look for.

The previous largest survey of discs was reported in a remarkable, but largely unremarked paper by Gavazzi, Pierini & Boselli (1996) entitled The phenomenology of disc galaxies. They found (a) the mass-to-light ratio in the near-infrared (NIR) is virtually constant and equal to 4.6 in H-band solar units; (b) Population I indicators are all anticorrelated with mass; (c) conversely the luminosity and SB of old stellar populations all increase with mass; (d) bulge components all increase non-linearly with mass; (d) the above properties are independent of either morphological type or environment.

Previous blind H\textsc{i} surveys, with follow-up optical or NIR data, have been carried out by Zwaan et al. (1997), Spitzak & Schneider (1998), Rosenberg & Schneider (2000), Minchin et al. (2003), Davies, Sabatini & Roberts (2004) and Giovanelli et al. (2005). Some of the results are discussed in Rosenberg & Schneider (2003), Minchin et al. (2004) and Rosenberg, Schneider & Posson-Brown (2005). The main results can be summarized briefly as follows:

(i) all but one galaxy (Minchin et al. 2005, 2007) seem to have optical counterparts;
(ii) although spirals predominate, the counterparts cover a wide variety of morphological types and luminosities;
(iii) there are significant, but not overwhelming, numbers of LSBGs;
(iv) to within the measurement errors all H\textsc{i} galaxies have the same H\textsc{i} column densities ($\sim 10^{20.65+0.38}$ cm\textsuperscript{-2}) and this is not a selection effect.

The various surveys differ from one another partly in radio sensitivity, but mainly in the quality of their optical or NIR follow-up data. Our ES is distinct in two main respects: (a) we have been fastidious in rejecting all sources where there might be more than one galaxy in or near the beam; (b) we have available high-quality multi-band SDSS-DR2 data for every source, data which are both sensitive and
uniform, across a wide dynamic range. Rosenberg et al. (2005) have attempted a similar analysis using, instead of optical, Two Micron All Sky Survey (2MASS) J-band data.

Our most interesting results can be summarized as follows. (a) All galaxies have the same mass-to-light ratio in H I-band solar units. In other words Gavazzi’s law holds over a dynamic range of 8 mag in absolute luminosity even in H I-selected galaxies free of optical selection effects. (b) There is a clear correlation between SB and luminosity. Combined with (a) it reveals a correlation between dynamical mass and optical radius cubed, again over a large dynamic range, but now with more scatter. In other words there is roughly constant global density for galaxies (≈1 × 10⁻²⁴ g cm⁻³). The virial theorem then implies the same angular velocity ≈4 × 10⁻¹⁰ rad s⁻¹, implying they could have rotated no more than 40 times in a Hubble epoch. (c) All the galaxies have the same global surface density in H I, that is to say the same H I mass divided by optical radius squared (R²). (d) All the galaxies have exponential profiles throughout most of their extents so that R_{200} is correlated very tightly with R_o. (e) There is a clear colour–luminosity correlation in the sense that more luminous galaxies are redder, which is well known in optically selected samples.

The remainder of this paper is arranged by section as follows.

(2) The Radio Observations describe the H I survey, the detection process and the contents of the resulting catalogue.

(3) The Optical Observations looks into the sensitivity of the SDSS for picking up large angular size LSBGs, and galaxies with low (M_{HI}/L_o) ratios. It then discusses the general problem of identifying reliable optical counterparts to H I sources in blind H I surveys.

(4) The Diversity of Sources displays complete data sets for a handful of detected objects, ranging from giant spirals to inchoate LSBGs, which represent important H I-selected class types. A montage of the optical counterparts illustrates their very wide variety. Finally, the complete data set is laid out in the form of tables.

(5) The Correlations in Galaxy Properties reveals the five separate correlations among their properties.

(6) The Discussion argues that the correlations, despite the small size of the sample, are significant, not unduly affected by distance uncertainties, and compatible with the Tully–Fisher relation: linewidth ~L_o, provided a ≈ 1/3. If no more than six physical invariants control galaxies, as we argue, then five correlations suggest a degree of organization among gas-rich galaxies which is surprising, and which must strongly constrain theories as to their formation and evolution.

2 THE RADIO OBSERVATIONS

The observations were carried out with the Parkes 64-m radio telescope using the Multibeam System (Staveley-Smith 1996) in which 13 adjacent beams employing 26 receivers track the sky at a rate of 1° min⁻¹, returning several times to the same piece of sky every week apart to minimize interference. The main characteristics of the survey are listed in Table 1.

The HIPASS catalogue, that is to say the pipeline catalogue of sources based on this raw data, has been released over the years using techniques, and with results described in Barnes et al. (2001), Meyer et al. (2004), Zwaan et al. (2004) and Wong et al. (2005). Our ES, based on the same raw data, but covering only 5700 deg² around the Equator (Garcia-Appadoo 2005) was analysed much earlier (1999) with the intention of providing an early source list in time for SDSS-DR2 release. Although it used almost identical search methods to HIPASS, and indeed copies most of them directly, it appears marginally more sensitive than the HIPASS catalogue of the same region (Wong et al. 2005), perhaps because we had more time to follow up marginal detections with the more sensitive narrow-band system at Parkes (Zwaan et al. 2004) thus winning fainter signal from noise. The ES covers 14 per cent of the entire sky in a band right round the celestial equator from declination –6° to +10°. Of this area about 1700 deg² is covered by the DR2 of the SDSS (Abazajian et al. 2004) which we will use as our source of optical information, Fig. 1 shows the distribution of sources around the sky, both those with SDSS-DR2 optical data and those without. The gaps caused by the Galactic plane, as well as the strong peak at a right ascension (RA) of ~12° due to the southern extension of the Virgo cluster are easily visible. Note that the source at ~20° RA lies in an additional small area of SDSS-DR2 coverage that, due to its small size, is not shown in Fig. 1. Fig. 2 shows the distributions of ES sources in both peak and integrated flux. As can be seen the distributions for both the ES sample with (hashed) and the sample without (clear) optical data are very similar. This indicates that the optical subsample we will be analysing here is representative of the sample as a whole and hence can be used to characterize the properties of H I selected galaxies in general.

The noise in the Parkes Multibeam data is complex, consisting of a mix of receiver noise, solar side-lobe emission, confusion and ripple in the 21-cm spectra with a characteristic frequency of ~1200 km s⁻¹ due to standing waves set up between the dish surface and the prime focus cabin by continuum sources in the beam. With such complex noise the selection effects which enter into the discrimination of weak sources cannot be anticipated, and must be recognized retrospectively. Multibeam data are presented to the observer in cubes with axes in the RA, Dec. (declination) and radial velocity directions. The cubes are 8° on a side separated into 4 arcmin pixel and divided in the third dimension to 1024 velocity channels each 13.1 km s⁻¹ wide. Given that the original radio beam was 7 arcmin half-maximum in diameter the pixel signals are partially correlated, as are the velocity channels which have been Hanning-smoothed to 18 km s⁻¹. These cubes (102 of them in our case) were searched individually using a mixture of numerical algorithms and the eye–brain system. Algorithms are helpful, particularly in reducing labour; but none has so far proved anywhere as reliable or sensitive as the eye–brain (e.g. Kilborn 2002). Each cube can be represented in three combinations (α, δ, V) and (δ, V) where V is the radial velocity, and all three are searched before deciding a source is probably present. Such probable sources can be followed up by using the multibeam system in a more sensitive narrow-band mode. A combination of much higher velocity resolution (1.3 km s⁻¹ per channel) and the ability to integrate

| Parameter | HIPASS value |
|-----------|--------------|
| Sky coverage | δ < +25° |
| Integration time per beam | 450 s |
| Average FWHM | 14.3 arcmin |
| Gridded FWHM | 15.3 arcmin |
| Pixel size | 4 arcmin |
| Velocity range | −1280 to 12700 km s⁻¹ |
| Channel separation | 13.2 km s⁻¹ |
| rms noise | 13 mJy beam⁻¹ |
| 3σ H I mass limit⁵ | 10⁶ D^2_{50} M_{⊙} |
| N_H I limit⁶ | 7.8 × 10¹⁸ cm⁻² |

⁵For ΔV = 100 km s⁻¹.
indefinitely on a possible source, rather than for a total of 450 s in the scans, is a powerful filter against spurious misidentifications (Zwaan et al. 2004). Note that the existence, or otherwise, of an optical counterpart is in no sense used in selecting or rejecting a source, making the survey truly blind.

The ES H\textsc{i} sample was selected using methods almost identical to HIPASS selection (Meyer et al. 2004; Zwaan et al. 2004). The noise is complex so the only way to establish the likely reality of sources is to follow up a sufficient proportion with the more sensitive ‘Narrow-band System’. The hundreds of putative HIPASS sources followed up gives confidence that significantly less than 5 per cent of the remaining ES sources could be spurious, far too small fraction to affect the correlations we are searching for (Section 5).

Fig. 3 shows the integrated flux as a function of the velocity width of the sources. It appears that detection by integrated flux is dependent on linewidth, with broad line sources being harder to find in the noise. In peak flux, however, it is much easier to set a clean selection criterion independent of linewidth (see Fig. 4), as Kilborn (2002) and other searchers in the multibeam data have found.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig1a.pdf}
\caption{(a) Distribution of R.A.'s}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig1b.pdf}
\caption{(b) Distribution of Declinations}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig2a.pdf}
\caption{(a) Distribution of peak fluxes ($S_{peak}$)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig2b.pdf}
\caption{(b) Distribution of integrated fluxes ($S_{int}$)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig3.pdf}
\caption{Selection limits in velocity width-integrated flux space. The theoretical $3\sigma$ limit for selection based on $S_{int}$ (constant signal-to-noise) is shown by the dashed line and the $3\sigma$ limit for $S_{peak}$ selection ($S_{int}/\Delta V_{50}$) is shown by the solid line. Most error bars have been omitted for clarity.}
\end{figure}
Fig. 5 shows flux limited curves \(N(S) \sim S^{-5/2}\) filled to peak fluxes (a) and integrated fluxes (b). Fig. 5(a) is suggestive of a peak-flux completeness limit \(\sim 50\) mJy.

The raw velocities are corrected for solar motion relative to the Local Group. The resulting distribution of radial velocities is shown in Fig. 6. Approximate distances are derived in a similar way as in Koribalski et al. (2004), using \(D = \frac{v_{LG}}{H_0}\), where \(v_{LG} = v_{sys} + 300 \sin l \cos b\), \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) is assumed throughout (and where necessary a cosmology with \(\Omega_m = 0.3\) and \(\Omega_{\Lambda} = 0.7\)).

The H\(_i\) masses were derived from the integrated fluxes using fitting processes identical to HICAT and

\[
M_{H_i}(M_\odot) = 2.36 \times 10^5 D(Mpc)^2 \int S(H_i) \, dV, \tag{3}
\]

where \(D\) is the distance in Mpc and the integral \(\int S(H_i) \, dV\) is the integrated flux in Jy km s\(^{-1}\), equation (3) assumes that all the sources are optically thin and that the upper limits of the 21-cm transition are fully excited. Fig. 7 shows the distribution of H\(_i\) masses for the ES sample.

Although in this paper we are not going to try and compensate for H\(_i\) selection effects we need to be aware of how they may have shaped our sample. The first worry concerns column density sensitivity. Will we have sufficient sensitivity to pick up LSBGs with correspondingly low \(N_{H_i}\) (see equation 2)? It can be shown (Minchin et al. 2003) that the column density sensitivity, \(N_{H_i} (\text{cm}^{-2})\), of any survey can be worked out retrospectively from the fluxes \(F\) (Jy km s\(^{-1}\)) and sizes \(\delta\theta\) (H\(_i\) diameter in arcmin) of the faintest sources within it according to

\[
[N_{H_i}]_{\min} = 4.5 \times 10^{20} \left( \frac{F_{H_1}}{\Delta V \delta \theta^2} \right)^{0.3} \Delta V \text{ atom cm}^{-2} \text{s}^{-1}, \tag{4}
\]

where \(\Delta V\) is their velocity width in km s\(^{-1}\). This is the H\(_i\) equivalent of equation (1) in the optical. For the ES it corresponds to \(\sim 10^9\) cm\(^{-2}\), or a low SB limit, according to equation (2), where \(\overline{\sigma}_{21}\) is the mean SB inside the 21-cm area of the galaxy:

\[
\overline{\sigma}_{21}(B) = 27 - 2.5 \log \left( \frac{N_{H_i}}{10^{20}} \right) \left[ \frac{M(H_i)}{L_B} \right] \text{ mag arcsec}^{-2}. \tag{5}
\]

For a typical \(M_{H_i}/L_B \sim 1\) this corresponds to a central SB \(\mu_{21}(B) \sim 25.7\) or an effective SB \(\mu_{eff}(B) \sim 27.5\) which is very dim, dimmer than any optical catalogue covering a significant area (see Table 3 for definition of different SBs). Indeed it is so dim that one might question whether the SDSS could reach it. However, here enters a surprising result recently discovered by Minchin using the Parkes Multibeam to carry out a much deeper H\(_i\) survey (HIDEEP; 9000 s beam\(^{-1}\)) of a small area, and with full optical follow up (Minchin et al. 2003) as did Rosenberg et al. (2005). Despite its great sensitivity to low column densities (\(N_{H_i} \geq 2 \times 10^{18}\) atom cm\(^{-2}\)) they found that there are no low column density galaxies. Indeed they found that all H\(_i\)-selected galaxies have, to within the errors, the same column density (\(\sim 10^{20.5}\) cm\(^{-2}\) if spread over five effective radii, as in optically selected samples; Salpeter & Hoffman 1996), see Fig. 8. We find the identical uniformity of \(N_{H_i}\) in the ES, see Fig. 9.

Whatever the reason for Minchin’s strange law (Minchin et al. 2003), and it needs explaining, the dimmest LSBGs we can expect to encounter in the ES will have, according to equation (5), and the fact that \(\overline{\sigma}_{eff} = \overline{\sigma}_{21} - 2.1\) mag for an exponential disc:

\[
\mu_{eff}(B) \text{ (mag)} = 23.9 + 2.5 \log \left( \frac{M(H_i)}{L_B} \right). \tag{6}
\]
Correlations among H\textsubscript{i}-selected galaxies

Figure 6. (a) The recessional velocity distribution of the ES sample. (b) The distribution of the 50 per cent velocity widths ($\Delta V_{50}$) for the ES sample. The unfilled histogram indicates those H\textsubscript{i} sources without optical data and the line-filled histogram the sources with optical SDSS-DR2 data.

Figure 7. Distribution of H\textsubscript{i} masses for the ES sample.

Figure 8. The distribution of the $N_{\text{HI}}$ column densities among the $\sim$100 HIDEEP galaxies from Minchin et al. (2003). The dashed line shows the sensitivity limit. There appear to be no low column density objects.

which should be comfortably accessible with SDSS for galaxies with $(M_{\text{HI}}/L_B)_{\odot} < 5$ (see Section 3).

The H\textsubscript{i} properties obtained for the ES sample are listed in Table 2, which is provided in full in the electronic edition of this journal. The columns are as follows.

Column (1) – ES source name.
Columns (2) and (3) – fitted H\textsubscript{i} positions in RA and Dec. (J2000).
Column (4) – H\textsubscript{i} peak flux density, $S_{\text{peak}}$.
Column (5) – integrated H\textsubscript{i} flux density, $S_{\text{int}}$.
Column (6) – H\textsubscript{i} systematic velocity, $v_{\text{sys}}$, measured at the 20 per cent level of peak flux density.
Column (7) – velocity linewidth, $W_{20}$, measured at 20 per cent level of the peak flux.
Column (8) – distance, $D$, in Mpc (see text for description).
Column (9) – the logarithm of the H\textsubscript{i} mass, $M_{\text{HI}}$, calculated using equation (3) in units of solar masses.

Figure 9. The distribution of column densities for the ES sample where the densities are obtained by assuming $\theta_{21} = 5 \times \theta_{50}$ (opt) – see text.
3 OPTICAL IDENTIFICATION AND OBSERVATIONS

We determined that the best source of optical data to follow up the radio survey would be the SDSS. With its five photometric bands (u, g, r, i, z), it offers a unique and homogeneous data base. The SDSS was, however, initially aimed at working on small faint objects and the pipeline software was not designed to cope with the arcminute-sized galaxies which turn up in the ES so that up to now most SDSS galaxy work has had to be confined to objects beyond z = 0.02 (e.g. Blanton et al. 2003). Identifying the various large galaxy problems, finding and validating solutions for them and rewriting parts of the software has held up the ES for at least 2 yr. This is no place to discuss those corrections as an account appears in West et al. (2009). We summarize them only briefly to emphasize how necessary they are when using SDSS to study galaxies of arcminute size.

3.1 Limiting surface brightness

One legitimate concern about the SDSS, which is a relatively shallow survey (∼55 s exposure per point), is whether it will go deep enough to detect the kind of LSBGs one might hope to find in the ES. Tests show that the main source of noise in looking for dim extended objects in the SDSS is photon noise in the sky subtraction (Strateva et al. 2001; West et al. 2009). In that case it can be shown that

\[ f(a) \geq \left( \frac{S}{N} \right) \frac{1}{\sqrt{N(a)}} \left( \frac{1}{\sqrt{N(a)}} \right) \]

(7)

where \( f(a) \) is the fraction of the sky level one can go down to and find objects of angular size \( \theta' \) (degree in arcsec) with a given signal-to-noise ratio (S/N) \( f(a) \) is that fraction for filter \( a \), while \( N(a) \) is the total number of photons accumulated from the sky arcsec^{-2} through filter \( a \). For the g-band SDSS \( N(g) \sim 120 \), and if one demands a S/N of at least 10 for detection:

\[ \bar{\mu}_{21}(g) \leq 22.1 + 2.5 \log_{10} \theta'. \]

(8)

For mapped galaxies the \( \theta'_{21} \) is typically 10 \text{''} \theta''_{50} \) where \( \theta''_{50} \) is the half light radius (e.g. Salpeter & Hoffman 1996). As \( \bar{\mu}_{21} = \mu_0 + 3.84 \), detection with SDSS in the g band requires

\[ \mu_0 \geq 20.8 + 2.5 \log_{10} \left( \theta''_{50} \right). \]

(9)

In contrast LSBGs are generally defined to have \( \mu_0(B) < 23.0 \) (see below). In other words, as you would expect of such a short exposure survey, the SDSS will be capable of picking up LSBGs only if they have large angular size (\( \theta''_{50} > 10 \text{arcsec} \)). In the case of the ES all the sources are nearby (\( < 10,000 \text{km s}^{-1} \) away) and although some of our claimed identifications lie close to the SB detection limit (8), they appear visible because they have patches of light that are brighter than average, such as H I regions. Of course we will not detect galaxies with relatively small fractions of H I, dEs and dSphs for instance, unless the galaxies are very massive. We can quantify this limitation by combining (9) with (5) in which case, for typical values of \( \log N_{\text{HI}} \sim 20.5 \text{cm}^{-2} \) (Minchin et al. 2003) and sky brightness, \( \mu_{\text{sky}}(g) = 22.5 \text{ g mag arcsec}^{-2} \), the ES will only detect galaxies for which

\[ \theta''(g)/(\bar{\mu}_{\text{HI}}/L_B)C \geq 15''. \]

(10)

where \( \theta'' \) is the optical diameter (corresponding to 2 \text{''} \theta_{50} \) in the g band. Gas-poor galaxies will only be found if they are close by (i.e. \( \theta'' \) large). In other words the ES may miss a significant fraction of light in the Universe coming from gas-poor galaxies. It is no coincidence that all but one of the galaxies we do detect appear to be late type.

Many definitions of galaxy SB, and what constitutes low SB, appear in the literature. For instance there are two quite different definitions of effective SB that are current: \( \mu_0 \), which is the actual SB at the half-light radius, and \( \bar{\mu}_{50} \), which is the mean value of the SB within the half-light radius. To avoid even further confusion we list all these definitions together in Table 3 and relate them all to the central SB \( \mu_0 \). The relationships are only valid for pure exponential profiles. Where we have converted from SDSS colours to \( B \sim V \) system we have used Cross et al. (2004).

Table 3. Definitions of SB for galaxies with pure exponential profiles.

| SB measurement | Definition |
|----------------|------------|
| \( \mu_0 \) | Central SB |
| \( \mu_{50} \), \( \mu_{90} \) | The SB at the half-light radius (sometimes called ‘effective SB’) |
| \( \bar{\mu}_{50} \), \( \bar{\mu}_{90} \) | The mean SB within the half-light radius (also called ‘effective SB’) |
| \( \mu_{0.5} \), \( \mu_{3.9} \) | The SB at the 90 per cent light radius |
| \( \bar{\mu}_{0.5} \), \( \bar{\mu}_{2.3} \) | The mean SB within the 90 per cent light radius |
| \( \bar{\mu}_{21} \), \( \mu_{3.84} \) | The mean SB within the outermost 21-cm contour (see text) |

Note. \( \mu_0 \) in magnitudes corresponds to the central SB \( I_B \) where \( I(r) = I_B e^{-r/\alpha} \) and \( \alpha \) is the scalelength.

Their total luminosity \( L_T = 2\pi I_0\alpha^2 \); \( R_{50} = 1.68 \alpha \), \( R_{90} = 2.32 R_{50} \) and (empirically) \( R_{21} \approx 5 R_{50} = 8.4 \alpha \).

346 D. A. Garcia-Appadoo et al.
What constitutes a LSBG must be a matter of convention. However, most optically selected surveys show a distribution in SB, however defined, which is approximately Gaussian with a FWHM $\sim 3.0$ mag. Thus galaxies with a SB 1.5 or more magnitudes dimmer than the peak value could reasonably be defined as LSBG’s and that seems to be a common, though not universal, convention (e.g. Impey & Bothun 1997). For photographic, and for shallow CCD surveys, the peak in the disc SB distribution appears to lie close to the Freeman value of $\mu(B) = 21.65$. Thus any disc dimmer than $\mu(B) = 23.0$, $\mu(B)$ could reasonably be regarded as LSB. The median SB for the ES, allowing for average bulge-to-disc ratio of $\sim 0.1$, is $\mu(B) \sim 22.5$ mag arcsec$^{-2}$, or about 0.8 mag arcsec$^{-2}$ dimmer than the Freeman value for optical surveys, and we find objects as dim as $\mu(B) \sim 24$ mag arcsec$^{-2}$.

### 3.2 Identification of optical counterparts

The unambiguous identification of optical counterparts to 21-cm sources found in a blind survey like ours is by no means trivial. Because of the strong clustering of galaxies, both in angular and in redshift space, it is all too easy to find a plausible optical counterpart for virtually every 21-cm source. It is surprising, for instance, that in HOPCAT, the published optical catalogue for the 4315 HIPASS sources in the Southern sky (Doyle et al. 2005) there is not one source, not one intergalactic gas cloud or dark galaxy without a plausible optical counterpart. We shall now estimate the rate of false identification, i.e. the probability of finding a random optical galaxy within a given distance, in both angular and redshift space, of any given HI source. We shall assume, as the observations clearly suggest (Staveley-Smith 1996) that optical galaxies and HI sources are clustered together. For an ES or HIPASS source the acceptable volume $V_{\text{acc}}$, in which an optical counterpart could lie is a long thin cylinder, centred on the source, with its long axis, set by the radial-velocity uncertainties, along the line of sight. For an ES source at a typical radial velocity of 2000 km s$^{-1}$, the angular uncertainties in position ($=R_0$) (up to 1 arcmin) correspond to $\sim 50$ kpc, while the velocity uncertainties $\Delta V$, taking account of both radio and optical uncertainties, amount to $H_0 \Delta V$ ($\sim 30$ km s$^{-1}$) ($=h$) or half a Mpc. Given the correlation function:

$$p(r) dV = n_0 dV [1 + \xi(r)],$$

where $\xi(r) = (r/r_0)^{-1.8}$ and $n_0$ is the average number of plausible galaxies Mpc$^{-3}$, it is possible to integrate the probability of finding a random galaxy within the volume $V_{\text{acc}}$ of the acceptable cylinder. To a very good approximation the number within a projected distance $R_0$ (in Mpc) of the source is given by

$$N(<R_0) \approx 1.8 n_0 r_0^{1.8} R_0^{1.2} (r_0 \approx 8 \text{ Mpc}).$$

Notice that the number is only weakly dependent on $R_0$ (because of the strong correlation) and dependent on the radial-velocity uncertainty not at all. This last is counterintuitive but arises from the long thin shape of the cylinder. The ends of the cylinder are so very far from the centre that finding highly correlated galaxies within the ends is very unlikely. Conversely, obtaining very accurate optical velocities for plausible galaxies in the field does not greatly enhance ones chances of making an unambiguous identification when the HI velocity uncertainties may still (for S/N reasons) be larger (and oddly enough, making blind HI surveys with bigger dishes will not help because the characteristic sources will be proportionately farther away; Disney 2008).

To turn equation (12) into numbers it is necessary to adopt an optical luminosity function for the putative galaxies. If we adopt

$$\varphi(M) = \varphi_* \alpha e^{-\alpha M},$$

where $\alpha = 10^{\alpha - 5} M_{\odot}$, $\alpha = 1.2$, $\varphi_* = 2.1 \times 10^{-2} h^{-3}$ and $M_* = -20.40 - 5 \log h$ (Blanton et al. 2003) then Table 4 where column (1) gives the angular size distance in Mpc, $R_0 = D\Delta_\theta$, $D$ is the source distance in Mpc, $\Delta_\theta$ is the angular distance between the source and the optical counterpart in radians and column (2) is the number of random galaxies (down to 3 mag below $M_*$) to be expected within that distance. As an example, consider a source at a typical radial velocity distance of 2000 km s$^{-1}$ in ES ($\sim 27$ Mpc) where 1 arcmin corresponds to $\sim 8$ kpc. The typical positional uncertainty in HIPASS $\sim 1.3$ arcmin (Meyer et al. 2004; Zwaan et al. 2004) corresponds to $\sim 0.01$ Mpc. At that distance, according to column (2) of Table 4, there is a 10 per cent chance of finding a random galaxy of roughly the right radial velocity, i.e. clustered with the HI source, within the positional uncertainty. Furthermore, the chance of a misidentification could be higher still if one was prepared to consider, as plausible candidates, objects more than 3 mag below $L_*$ in the luminosity function (our assumption in Table 3). Note that Doyle et al. (2005) identify optical candidates up to 5 arcmin away, leading to the probability of a plausible misidentification at that distance of more than 1.

To reduce these potentially serious misidentification problems in ES we threw out all (90 out of 310) sources which looked, on inspection of the SDSS-DR2 fields, to have more than one plausible optical counterpart within the radio beam (FWHM $\sim 14$ arcmin) and we obtained accurate optical velocities for all the rest using either those provided in NED, the SDSS-DR2 fibre or, for 20 galaxies, the Dual Imaging Spectrograph on the 3.5-m telescope at Apache Point Observatory. All candidates with optical velocities discrepant from the HI value by more than half the 21-cm linewidth $\Delta V_{21}$ were discarded. In addition, a number of other sources were removed either because they extended across two or more SDSS-DR2 fields, or because there was a saturated foreground star within 1 arcmin.

Altogether of the original 310 HIPASS sources with plausible SDSS-DR2 galaxies within the HIPASS beam and at the right redshift (as defined above) 90 were thrown out because of multiplicity, i.e. for there being more than one (up to five) good SDSS-DR2 candidates, 20 were too extended and five too near a bright star. Fig. 10 shows the distribution of velocity differences $\Delta V/W_{21}$ for the original 310 candidates and Fig. 11 shows the distribution in positional differences between the radio and optical sources for the
195 which remain in the final ES list. The tail in this plot is due to the H\textsc{i} centroid not being centred in the optical source.

Most of the identifications fall within 2 arcmin of the radio position, consistent with the errors in those positions measured in the general HIPASS catalogue using interferometry (Meyer et al. 2004). Nevertheless, there remain a tail of optical candidates up to 7 arcmin (half the FWHM beam) away from the radio centroid. Because of clustering (see Table 3) we cannot rule out the possibility that a handful of sources (probably less than 10) remain misidentified. This is too small a number to invalidate the main results. Nevertheless, we should acknowledge biases in our sample against galaxies in tight groups (too many in the beam), galaxies that appear very large (overlapping SDSS-DR2 fields), and dark galaxies or intergalactic clouds for which we will too easily find plausible, optically bright alternatives. Most of these biases are difficult to avoid and must exist to an equal or greater extent in other H\textsc{i} selected blind samples. In particular the number of sources (~30 per cent) discarded because of clustering within the beam highlights the difficulty of measuring H\textsc{i} mass functions which are not somehow adjusted for confusion.

The data we used all came from SDSS-DR2 (Abazajian et al. 2004) using the pipeline from DR3 (Abazajian et al. 2005) but no SDSS catalogue data were used, for reasons outlined below. DR2 covers 3324 deg\textsuperscript{2}, about half of which overlaps the ES. SDSS pipeline photometry of large galaxies is very inaccurate for a number of reasons. The pipeline shreds large galaxies into a number of pieces, circular apertures are not appropriate, the inclination is not properly taken account of and worst of all sky subtraction can subtract much of a large galaxy away from itself. Thus we had to find ways of measuring the significance of all these problems and devise alternative methods of handling the data. These are discussed at length in West (2005) and are being published (West et al. 2009) so that the community wanting to use SDSS to work on nearby galaxies can make use of them.

Table 5 lists the SDSS-DR2 optical data for the ES sample.

| Table 5. Petrosian photometry of the ES sample. |
|-----------------------------------------------|
| ES name (J2000) | RA (J2000) | Dec. (J2000) | u | g | r | i | z | PetroR50 (arcsec) | PetroR90 (arcsec) |
| HIPEQ 0014–00 | 00 14 36 | 00 04 42 | 13.77 ± 0.04 | 13.13 ± 0.02 | 12.91 ± 0.02 | 12.82 ± 0.02 | 12.77 ± 0.03 | 21.4 ± 0.4 | 59.0 ± 0.8 |
| HIPEQ 0027–01a | 00 27 47 | 01 09 39 | 14.72 ± 0.04 | 14.09 ± 0.02 | 13.85 ± 0.02 | 13.79 ± 0.02 | 13.87 ± 0.04 | 21.4 ± 0.4 | 43.6 ± 0.8 |
| HIPEQ 0033–01 | 00 33 22 | 01 07 01 | 15.65 ± 0.06 | 14.86 ± 0.02 | 14.58 ± 0.02 | 14.44 ± 0.02 | 14.40 ± 0.05 | 20.2 ± 0.4 | 45.9 ± 1.6 |
| HIPEQ 0043–00 | 00 43 31 | 00 06 49 | 13.90 ± 0.03 | 12.95 ± 0.02 | 12.52 ± 0.02 | 12.31 ± 0.02 | 12.14 ± 0.03 | 13.9 ± 0.4 | 36.4 ± 0.4 |
| HIPEQ 0051–00 | 00 51 57 | 00 28 25 | 15.42 ± 0.03 | 14.60 ± 0.02 | 14.23 ± 0.02 | 14.06 ± 0.02 | 13.99 ± 0.03 | 6.3 ± 0.4 | 17.4 ± 0.4 |
| HIPEQ 0058+00 | 00 58 50 | 00 37 46 | 14.90 ± 0.03 | 13.91 ± 0.02 | 13.43 ± 0.02 | 13.19 ± 0.02 | 13.07 ± 0.03 | 10.7 ± 0.4 | 23.0 ± 0.4 |

Note. An extract of the table is shown here for guidance. It is presented in its entirety in the electronic edition of the journal.
Correlations among H I-selected galaxies

To consider the diversity of sources in more detail we consider four individual galaxies each representing a different characteristic ‘class type’ of object that is quite common in the sample. As a fiducial comparison one can pick say HIPEQ 1507+01 (NGC 5850) which is typical of the kind of galaxy that turned up in optically selected catalogues and which were afterwards examined at 21 cm (e.g. Huchtheiser & Richter 1998). It is optically very luminous, 1.7 mag brighter than \(L_*\), has a low \(M_{HI}/L_B = 0.15\) but nevertheless contains a significant amount of \(H I\) (log \(M_{HI} = 9.8\)) simply because of its high luminosity. It is early type \((T = 3)\), red \((g - r = 0.63)\) and dynamically very massive \((\log M_{\text{dyn}} = 11.7 M_\odot)\), where \(M_{\text{dyn}} = R_0(g) [W_{20} / \sin(i)]^2 / G\).

The greatest number of galaxies in the ES are late-type spirals a magnitude or so fainter than \(L_*\) but gas rich (i.e. median \(M_{HI}/L_B = 0.91 \pm 0.16\)) and blue.

(i) Our first \(H I\) selected type is a ‘Hydrogen Giant’, that is to say a galaxy with more than \(10^{10} M_\odot\) of \(H I\). HIPEQ 2036–04 (NGC 6941) contains \(2 \times 10^{10} M_\odot\), apparently an upper limit if one excludes other nearby companions – as here, and about five times the \(H I\) mass of the Milky Way (Binney & Merrifield 1998) (Fig. 12a). Their huge hydrogen content means that such galaxies can be detected far away and this one is at 6200 km s\(^{-1}\). It is also a giant optically, being \(\sim 3 L_*\) in g but its gas-to-light ratio is \(M_{HI}/L_B = 0.7\) that is five times higher than the fiducial value for giants. Fig. 12(a) shows an SABb \((T = 3)\) with a high SB core but a low SB disc with widely spread spiral arms. The integrated colour is \((g - r) = 0.79\), while the fibre spectrum of the core is typical of an early-type spiral. What is remarkable about these Hydrogen Giants is that they appear to have slowed their star formation and so still contain as much mass in gas as in stars. The dynamical mass is high \((\log M_{\text{dyn}} = 11.3)\), but 1.5 times less than NGC 5850, the fiducial galaxy. There are 20 in the survey, but given their generally high redshifts (median \(\sim 5500\) km s\(^{-1}\)) hydrogen giants cannot be common in space. The astrophysical challenge is to explain their delayed evolution from gas into stars.

(ii) Our second class type is the LSBG of the more massive kind – typically an anaemic spiral like HIPEQ 1303+03 (UGC 08153)
shown in Fig. 12(b) (other good examples are HIPEQ 1228+02 and 2337+00). It is truly low SB with a $\mu_{50}(g) = 24.3$ and yet its dynamical mass is $10^{10} M_\odot$. Formally speaking there are even more massive LSBGs in the sample but their discs are so extremely dim that estimating an accurate axis ratio, necessary to calculate a dynamical mass, often becomes problematic. The total luminosity is $0.5 L_\star (M_\star = -18.8)$ and the hydrogen content is $\log_{10} M_{\text{HI}} = 9.0 (M_{\text{HI}}/L_B = 0.77)$. The colour is blue, $(g - r) = 0.27$, as is commonly the case with LSBGs (McGaugh & Bothun 1994) but there are also some redder ones in the survey. The question of how significant LSBGs are in cosmic terms (e.g. Fukugita et al. 1998) hinges upon two difficult questions: on how massive they are and how common. HIPEQ 1303+03 and its like confirm, beyond question, that true LSBGs can be massive (see also Sprayberry et al. 1993). To what extent blind H$\alpha$ surveys can compensate for the dramatic selection effects against LSBGs in optical catalogues is not yet clear. Certainly such surveys find healthy numbers of LSBGs. However, Fig. 13 shows that although $N_{\text{HI}}$ is more or less constant in the sample, there is a perceptible fall-off in the column density with SB, with a sharp cut-off at $10^{19.3} \text{H} \alpha$ atom cm$^{-2}$. This is due to the instrumental limit of the Multibeam system for 400-s integration so it could still be missing some low SB objects (see Minchin et al. 2004). There are $\sim 10$ LSBGs with dynamical masses $> 10^{10} M_\odot$, and as many again which are just as dim apart from a small bright core.

(iii) Our third type is the irregular for which HIPEQ 0821-00 (UGC 04358) in Fig. 12(c) serves as an example though they are very heterogeneous. ES irregulars are naturally gas rich, HIPEQ 0821-00 having $(\log M_{\text{HI}} = 9.3$) almost as much H$\alpha$ as the Milky Way with an $M_{\text{HI}}/L_B = 3.3$. At $M_\star = -16.4$ it is $\sim L_\star/20$, has a very blue colour $[(g - r) = 0.17]$ and moderately high SB $[\mu_{50}(g) = 22.5]$ though SBs among the type vary by 5 mag and global SBs for such irregular objects are rather meaningless. There are at least 30 irregulars in the ES sample.

(iv) The last ‘type’, the ‘inchoates’, are so dim and faint that they could scarcely be found in any other but a blind H$\alpha$ survey. Our example HIPEQ 1145+02 (Fig. 12d) can barely be seen on the SDSS, having a SB $\mu_{50}(g) = 24.8$ at the very limit of the survey. We detect it only because it has a lot of hydrogen for its luminosity ($M_{\text{HI}}/L_B = 7$) which at $M_\star = -14.31$ is $1/200 L_\star$. The ‘inchoate’ label for these objects derives from their apparent total lack of organization. More irregular than irregulars, they have no cores or obvious centres, and appear as merely haphazard enhancements of SB at what appear to be H$\alpha$ regions. In addition to being extremely gas rich ($M_{\text{HI}}/L_B > 5$) they are generally blue, thus HIPEQ 1145+02, by no means extreme in colour, has $B - V = 0.48$ and $(g - r) = 0.27$. Other good examples of what is a virtually new type of galaxy are HIPEQ 0238+00, 0240+01, 0958+01, 1227+01 and 1256+03. We say ‘virtually’ because one of them, HIPEQ 1227+01, is the famous cloud serendipitously found by Giovanelli & Haynes (1989) and at first thought to be a protogalaxy. Indeed it would have been the easiest inchoate to find as it has the highest $M_{\text{HI}}/L_B (~22)$ of any object in the ES sample.

Now that we have a dozen or so ‘inchoates’ in the ES to study, some of the puzzling questions raised by the original Giovanelli and Haynes cloud return with even greater insistence. It is the combination of their properties which makes it difficult to explain inchoates (Salzer et al. 1991; Grossi et al. 2007). Their extraordinarily high gas-mass fraction indicates little integrated past star formation, while their blue colours [as blue as $(B - V) \leq 0.3$] can only be explained with star formation that rises sharply to the present day (Bruzual & Charlot 2003). However, if such a rise is only a temporary burst, then the galaxies should soon fade by 1.5 mag while reddening from $(B - V) = 0.3$ to 0.5, leaving behind an optically undetectable dark H$\alpha$ cloud (Leitherer et al. 1999). However, there are no such dark clouds in our survey, and none among 4315 HIPASS sources detected across half the sky (Doyle et al. 2005), all of which are optically detected in either SDSS or the SuperCosmos Sky Survey (Hambly et al. 2001). Thus a bursting explanation for their blue colours seems less likely than either a truly young galaxy or a steadily rising star formation rate. However, GALEX measurements of two of them (1145+02 and 1256+03) imply current star formation rates that are only a factor of $\sim 2$ greater than the past average. Furthermore, if they were truly young, why do not blind H$\alpha$ surveys like HIPASS find their predecessor dark protoclouds? ‘inchoates’ are indeed a puzzle.

Whatever they are, inchoates make a dramatic contrast with fiducial galaxies like NGC 5850 and with the higher SB spirals which make up more than half the sources in the ES sample. Together with luminous gas-poor galaxies, hydrogen giants, massive LSBGs and irregulars they illustrate a diversity which suggests a wide scatter among several underlying fundamental parameters such as mass, age, angular momentum and binding energy. However, such turns out not to be the case.

### 5 Correlations among Galaxy Properties

We have measured nine quantities in all, combined with the inclination $b/a$ which can be used to correct observed quantities to face on: mass of H$\alpha$, H$\alpha$ linewidth (as defined in Section 2), luminosity (in $g$), four colours $(u - g)$, $(g - r)$, $(r - i)$ and $(i - z)$ and two radii $R_{20}$ and $R_{90}$ in $g$ band) all defined in Section 3. What we are chiefly missing is some kind of environmental parameter, which could be vital. However, we have been so fastidious in excluding closely packed galaxies that we cannot use environment for now. Later, with more interferometry of the dubious identifications within groups, we can add that to the study. Even so it is worth pressing ahead without it, provided we remember the caveat, because Gavazzi et al. (1996) showed that for the late-type galaxies which appear in the ES, environment appears to be unimportant.
From the nine basic measurements, and the inclination and assumed distance, one can construct other more familiar and perhaps more interesting parameters such as circular velocity \(V_0\), dynamical mass \(M_{\text{dyn}}(\sim V_0^2R_0/G)\), SB \(T_{\text{g}(g)}(\sim L_g/R_0^2)\), column density \(N_{H_1} \sim M(H_1)/R_0^2\), brightness temperature \(T_{H_1}(\sim N_{H_1}/\Delta W_{20})\), angular momentum per unit mass \((q \sim V_2R_0)\) and so on. With at least 15 such synthetic parameters to work with there are \(\approx (15 \times 14/2) \approx 100\) correlations to look for. We could have used some statistical technique but we elected to look at all the correlations by eye for now. Correlation coefficients, and their significance are given for each correlation. Thus one can discount obvious selection effects, and the already well-known correlations, to concentrate on looking for what might be new or surprising.

We are of course far from the first to attempt such a systematic search among galaxy properties. For instance Balkowski (1973), Brosche (1973), Tully & Fisher (1981), Gavazzi et al. (1996) and Blanton et al. (2003) looked at optically selected samples but with added \(H_1\) data, whilst Minchin et al. (2003), Rosenberg et al. (2005), Begum et al. (2006) and Kovac (2007) have recently looked at \(H_1\) selected sets followed up either by optical or by NIR measurements from 2MASS. Elsewhere we shall compare results, but for now we examine only our own correlations with an eye unbiased by previous work.

As a start it is important, given the rather small number in the sample (195), to establish that there is sufficient dynamic range within its intrinsic properties to make correlation analyses worthwhile. To look for relations between two galaxy properties \(x\) and \(y\), of the form \(y = Ax^n\), it is elementary to show that the error on \(m\) due to measurement errors \(\delta y, \delta x\), as opposed to real scatter in the properties themselves, is given by

\[
\sqrt{\frac{\delta m}{m}} \approx 1.5 \sqrt{\left(\frac{\delta y}{y}\right)^2 + \left(\frac{\delta x}{x}\right)^2},
\]

where \(\Delta \text{mag}\) \(\equiv 2.5 \log_{10}(x)\) and the \(\Delta \text{mag}\)s give the relevant dynamic ranges. Table 6 shows in column (1) the most relevant properties measured for the galaxies in the ES sample.

Table 6. Properties of the ES sample with optical SDSS-DR2 data.

| Property                | Median       | Min     | Max     | Range | Relative error |
|-------------------------|--------------|---------|---------|-------|----------------|
| Mass \(M_\odot\)        | \(10^{10.38}\pm0.40\) | \(10^{7.5}\) | \(10^{10.2}\) | 6.8   | 0.03           |
| Luminosity \((L_\odot)\)| \(10^{5.51}\pm0.38\)   | \(10^{7.2}\) | \(10^{10.6}\) | 8.5   | 0.01           |
| Area \((\pi R_g^2)\)    | \(10^{1.91}\pm0.1\)   | \(10^{-2}\) | \(10^{3.12}\) | 8.3   | 0.01           |
| Linewidth \(W_{50}\)   | \(10^{2.12}\pm1.78\)  | \(10^{-1.6}\) | \(10^{2.60}\) | 2.5   | 0.09           |
| SB \((T_{g}(g))^2\)    | \(10^{1.85}\pm0.07\)  | \(10^{1.08}\) | \(10^{2.99}\) | 5.2   | 0.01           |
| Dynamical mass \(M_\odot\)| \(10^{10.14}\pm0.53\) | \(10^{8.5}\) | \(10^{11.3}\) | 7.0   | 0.06           |
| Colour \((g-r)\)       | \(0.39\pm0.11\)       | 0.1     | 0.7     | 0.6   | 0.07           |

First notice that the four colours are strongly correlated (Fig. 14), as was to be expected, so there is considerably degeneracy among them and, as revealed already, to first order there is only one independent colour (Strateva et al. 2001). Many properties correlate with luminosity and Fig. 15 shows the colour–luminosity diagram, which is well known for optically selected galaxies, i.e. more luminous galaxies are redder. When it comes to disentangling the physics going on the actual slopes in all such correlation diagrams will be crucial. Thus Fig. 15 implies that \(L_y \sim L_x^{1.1}\) roughly. The Pearson

Figure 14. (a) Shows the relations between the \((u-g)\) and \((r-i)\) optical colours and (b) shows the relation between the \((g-r)\) and \((i-z)\) optical colours of the ES sample.
The $(g - r)$ colour/luminosity relation.

**Figure 15.**

The SB/luminosity relation in $g$ band. The dotted line shows the best linear fit to the data.

**Figure 16.**

The $r_p$ correlation coefficient is $r_p \sim 0.61$, corresponding to a probability $P(r > r_p) > 99.9$ per cent. This is the first of the five correlations.

Fig. 16 exhibits the second correlation ($r_p \sim -0.55$, $P(r > r_p) > 99.9$ per cent), i.e. between surface-brightness and luminosity and, not unexpectedly less luminous galaxies are dimmer. While this has been long suspected (e.g. Bingelli, Sandage & Tarenghi 1984) one could never be certain, in any optically selected sample, to what extent it was an artefact of the dramatic selection effects acting on SBs which lie so close to the sky (e.g. Disney 1999). However, here all the galaxies have been identified without regard to their optical properties and it seems very likely that Fig. 16 tells us something fundamental about the relation between luminosity and radius with few selection effects. While the scatter is large the correlation is clear and very roughly speaking the SB $\Sigma(r) \sim L_g^{0.5}$.

The third correlation ($r_p \sim 0.75$, $P(r > r_p) > 99.9$ per cent), between H$\alpha$ mass and optical radius, is illustrated in Fig. 17. It is a tight one and suggest that all galaxies have the same H$\alpha$ column density, i.e. $M_{H\alpha} \propto R_g^2$. This was discovered first by Haynes & Giovanelli (1984) in an optically selected sample, discovered again in an H$\alpha$ selected sample by Minchin et al. (2003) and confirmed in an interferometer study by Rosenberg et al. (2005) in the Arecibo Dual Beam Survey and Kovac (2007) and our ES measurements concurs. For now constant surface density is an intriguing puzzle which needs to be explained.

The fourth correlation ($r_p \sim 0.81$, $P(r > r_p) > 99.9$ per cent) we find is between luminosity ($g$) and dynamical mass shown in Fig. 18. Over more than three orders of magnitude the $g$ luminosity is tightly correlated with dynamical mass, a correlation that appears perceptibly tighter than the Tully– Fisher correlation which we show in Fig. 19 (see later). The slope is close to 1, implying a direct proportion between dynamical mass and luminosity. This is not new either but it was discovered in the remarkable paper by Gavazzi et al. (1996). In order to compare our data with Gavazzi’s, we transform ours into the H band, which should be freer of dust and of transient star formation effects. 113 of our ES sources are in 2MASS and Fig. 20 illustrates the relation between their colour and their luminosity, which implies

$$\log(L_H) = (1.31 \pm 0.05) \log(L_g) - (2.9 \pm 0.4),$$

i.e. $L_H \sim L_g^{4/3}$. If we use this to transform our Fig. 18 data into the $H$ band we reach Fig. 21 where our galaxies are plotted on top of the GOLDMine sample assembled by Gavazzi et al. (2003) for a mixture of bright discs and Virgo dwarfs. Over almost four orders of

The $H$-mass/radius correlation, i.e. constant column density. The dotted line shows the best linear fit to our data.

**Figure 17.**

The dynamical mass/luminosity relation in $g$ band. The dotted line shows the best linear fit to the data.

**Figure 18.**

The dynamical mass/luminosity relation in $g$ band. The dotted line shows the best linear fit to the data.
Correlations among H\textsubscript{I}-selected galaxies

353

Figure 19. The Tully–Fisher relation in $g$ band.

Figure 20. The ($g - H$) colour $H$-band luminosity relation for the ES galaxies detected by 2MASS.

Figure 21. The dynamical mass–$H$ band luminosity relation for our samples (circles) and for the GOLDMine sample (triangles).

Figure 22. The concentration index of H\textsubscript{I} galaxies as a function of luminosity. A best-fitting line has a slope of only $-0.017$. The ratio should be 2.32 for a perfect exponential disc.

6 DISCUSSION

We set out to look for correlations within a sample of galaxies free of optical selection effects. Apart from inclination and velocity we measured nine parameters for each galaxy. Since the four colours appear degenerate we are left with six a priori independent observables, between which we find the following five correlations, four old and one new (A) which are shown in Table 7, where the columns are as follows.

Column (1) – correlations observed.
Columns (2) and (3) – denote the distance dependence, $d_x$, of the left- and right-handed parameters in the correlation.
Column (4) – indicates the difference between the two exponents in columns (2) and (3) (see text for explanation).
Column (5) – shows the observables introduced into the correlation that have not been used before.

Column (5) in Table 7 is pertinent to the independence of the five correlations. Unless a priori reasons can be advanced for a dependence of the new observables on previous ones, then the five correlations must be independent. It might, for instance, be argued that $\theta_50$ should depend on $\theta_90$, but that ignores the real differences.
in ‘concentration’ \( q \equiv \theta_{90}/\theta_{50} \) between galaxies of different morphological type (e.g. \( q = 2.3 \) for pure exponential but \( q = 4.2 \) for de Vaucouleur profiles). Concentration is a crude but quantitative proxy for morphological type, and there is no a priori case for this to be the same among \( \text{H} \) sources. Thus we can argue that the five correlations must be partially, if not wholly, independent.

Although the number of galaxies is modest the dynamic range of most of their properties is large (i.e. more than 7 mag in luminosity, area, \( M_\text{H} \) and \( M_{\text{dyn}} \)) whilst the correlations are, in a statistical sense, highly significant. So far as the existence of the correlations (our main interest here) is concerned the sample size is not an embarrassment, though larger samples will be needed to pin down the slopes of the correlations more precisely. There is moreover a great diversity of galaxy types in the sample, ranging between early-type giant spirals and tiny ‘incohoates’ of such low SB that they would usually be, and indeed were, missed in optical surveys. The difficulty of making a reliable census of galaxies in light alone is illustrated by Fig. 16 where it can be seen that at all luminosities galaxies can vary in SB over 3 or 4 mag, making the dimmest of them, even the giants, hard to pick out from the background by optical means alone. The narrow SB range of earlier catalogues (Freeman 1970; Disney 1976) was almost certainly a selection artefact.

Two correlations in particular need explaining. Correlation (E), i.e. \( M_\text{H} \sim \rho_\text{dyn}^2 \) could be related to the stability of a gas layer to gravitational collapse, and hence to a trigger for star formation (e.g. Kennicutt 1989; Schaye 2008). The other, the SB/luminosity correlation (A) has considerable scatter (Fig. 16) making it difficult to pin down an accurate value for \( \beta \) in \( \Sigma \sim L^\beta \), where \( \beta \) is not far from 1/2. Combining our data with the GOLDMine sample, in order to increase sample size and hopefully reduce scatter, yields \( \Sigma \sim L^{1/3} \), or \( \Sigma \sim R \text{ or } L_\text{H}/R_\text{H}^2 = constant \) or, considering Gavazzi’s law, \( M_{\text{dyn}}/R_\text{H}^3 = constant \) (\( \sim 1 \text{ H atom cm}^{-3} \) within the optical radius) which, see Fig. 23(b), is a pretty good fit. So the mass – and luminosity – density of galaxies is more or less independent of their luminosity. This is at least a better mnemonic for recall of the rather transient SB/Lum law. If true then the virial theorem implies that all \( \text{H} \) galaxies spin at the same angular velocity and rotate \( \sim 40 \) times in a Hubble epoch.

What about the Tully–Fisher correlation \( \Delta V \sim L^\alpha \) Gavazzi’s law (C): \( L_\text{H} \sim M_{\text{dyn}} \equiv R_\text{H}\Delta V^2 \) while above: \( R_\text{H} \sim L_{\text{H}}^{1/2} \), hence \( \Delta V \sim L_{\text{H}}^{1/3} \). In other words our data are consistent with the TF law provided \( \alpha = 1/3 \) (see also Fig. 18). The problem with using TF directly is demonstrated in Table 6 where it can be seen that the low dynamic range in \( \Delta V \) will always make it difficult to find the exponent \( \alpha \) accurately, and it makes more sense to incorporate \( \Delta V \) into the dynamical mass (=\( R_\text{H}\Delta V \)) instead, as it is in Gavazzi’s law (C) where it leads to both a clear correlation with luminosity (Fig. 21) and perhaps a natural physical explanation (‘all galaxies are made of the same stuff’).

The distance to most galaxies in our radial velocity range can be problematic so it is important to ask if and how distance uncertainties will affect the correlations. Where there is a difference

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| A   | SB/Lum | \( d^0 \) | \( d^2 \) | 2 | SB, \( \theta_{90}, d \) |
| B   | Col/Lum | \( d^0 \) | \( d^2 \) | 2 | \( g-r \) |
| C   | \( M_{\text{dyn}}/L_\text{H} \) | \( d^1 \) | \( d^2 \) | 1 | \( \Delta V \) |
| D   | \( R_{90}/R_{20} \) | \( d^1 \) | \( d^2 \) | 0 | \( \theta_{90} \) |
| E   | \( M_\text{H}/R_{20}^3 \) | \( d^2 \) | \( d^2 \) | 0 | S (21 cm) |

**Table 7. Correlations in the ES sample.**

\[ \text{Figure 23. Top: the ratio } M_{\text{dyn}}/\rho_\text{dyn}^3 \text{ ratio as a function of the } g \text{-band luminosity. Bottom: the relation between the dynamical mass and } \rho_\text{dyn}^3 \text{ for our sample (circles) and for the GOLDMine sample (triangles).} \]
How constraining could the five discussed correlations (A to E) be on theories of galaxy formation and evolution? That depends on how many fundamental, independent invariant physical properties galaxies might possess. At present it is hard to imagine more than seven: total mass, baryon fraction, age, angular momentum, random energy, radius and central condensation. Once a galaxy has virialized, the virial theorem will provide one relation between them, leaving only six independent properties. Ignoring interactions one might expect, to first order, that these properties might be conserved by each galaxy though, on a secular time-scale some random energy might be dissipated, while some baryons might be ejected. Thus five correlations (if they are truly independent) within a six-parameter set hint at a high degree of organization among gas-rich galaxies, something partially foreshadowed by the early H I pioneers (Balkowski 1973; Brosche 1973). We have carried out a principal component analysis to investigate the degree of organization in this data and its implications (Disney et al. 2008).

On the observational front work in progress by us includes enlarging the sample size as more SDSS and H I data (e.g. from the Bonn 100-m Multibeam Survey; Kerp et al., in preparation) becomes available. Our automated SDSS photometric pipeline for large galaxies should greatly accelerate progress (West et al. 2009). H I interferometry is being obtained, first to sort out identifications in tight groups and second to measure more actual H I radii to get a better understanding of the Minchin–Rosenberg effect. So far we have exploited neither the colours nor the fibre spectra but work is in hand to include them too (West et al., in preparation). Statistical work on mean cosmic properties, such as the mean H I cosmic density, depends on a clear understanding of ones selection effects and this is underway too (Garcia-Appadoo et al., in preparation).

We are also working on the reverse list, that is to say a list of objects in the SDSS survey which we would have expected to contain measurable H I, and thus show up in the ES, but which do not (West & Garcia-Appadoo, in preparation).

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Table 2. H I properties of the ES sample.
Table 5. Petrosian photometry of the ES sample.

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