HIDEEP – an extragalactic blind survey for very low column-density neutral hydrogen

R. F. Minchin, M. J. Disney, P. J. Boyce, W. J. G. de Blok, Q. A. Parker, G. D. Banks, K. C. Freeman, D. A. Garcia, B. K. Gibson, M. Grossi, R. F. Haynes, P. M. Knezek, R. H. Lang, D. F. Malin, R. M. Price, I. M. Stewart and A. E. Wright

1 School of Physics and Astronomy, Cardiff University, 5 The Parade, Cardiff CF24 3YB
2 Astrophysics Group, Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL
3 Department of Physics, Macquarie University, Sydney, NSW 2109, Australia
4 Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston, ACT 2611, Australia
5 Centre of Astrophysics & Supercomputing, Swinburne University, Mail #31, PO Box, 218 Hawthorn, VIC 3122, Australia
6 School of Mathematics & Physics, University of Tasmania, Hobart, TAS 7001, Australia
7 WIYN Consortium Inc, 950 North Cherry Avenue, Tucson, AZ 85719, USA
8 Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia
9 Department of Physics and Astronomy, University of New Mexico, 800 Yale Boulevard NE, Albuquerque, NM, USA
10 Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH
11 Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

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ABSTRACT

We have carried out an extremely long integration time (9000 s beam$^{-1}$) 21-cm blind survey of 60 deg$^2$ in Centaurus using the Parkes multibeam system. We find that the noise continues to fall as $\sqrt{t_{\text{obs}}}$ throughout, enabling us to reach an HI column-density limit of $4.2 \times 10^{18}$ cm$^{-2}$ for galaxies with a velocity width of 200 km s$^{-1}$ in the central 32 deg$^2$ region, making this the deepest survey to date in terms of column density sensitivity. The HI data are complemented by very deep optical observations from digital stacking of multi-exposure UK Schmidt Telescope $R$-band films, which reach an isophotal level of 26.5 $R$ mag arcsec$^{-2}$ ($\approx 27.5$ $B$ mag arcsec$^{-2}$). 173 H I sources have been found, 96 of which have been uniquely identified with optical counterparts in the overlap area. There is not a single source without an optical counterpart. Although we have not measured the column densities directly, we have inferred them from the optical sizes of their counterparts. All appear to have a column density of $N_{\text{HI}} = 10^{20.65 \pm 0.38}$. This is at least an order of magnitude above our sensitivity limit, with a scatter only marginally larger than the errors on $N_{\text{HI}}$. This needs explaining. If confirmed it means that HI surveys will only find low surface brightness (LSB) galaxies with high $M_{\text{HI}}/L_B$. Gas-rich LSB galaxies with lower H I mass to light ratios do not exist. The paucity of low column-density galaxies also implies that no significant population will be missed by the all-sky H I surveys being carried out at Parkes and Jodrell Bank.

Key words: surveys – galaxies: distances and redshifts – radio lines: galaxies.

1 INTRODUCTION

Most of our knowledge of galaxy populations derives from samples collected in optical surveys, where there are strong selection effects. For instance, most of the galaxies we know about are barely brighter than the terrestrial sky, while galaxies that have lower surface brightnesses may be severely underrepresented. Attempts to overcome optical selection effects through the use of better detectors, larger telescopes, longer exposures and sophisticated image processing have met with partial success. This remains a very difficult process, however, and the subsequent corrections which have to be made to small number statistics are both large and controversial (e.g. Impey & Bothun 1997; Disney 1999).

Low surface brightness (LSB) galaxies could be significant in a number of contexts. They might add to or even dominate the luminosity-density and/or mass-density of galaxies as a whole (e.g.
Fukugita, Hogan & Peebles 1998). Additionally, they could be responsible for much of the metal line absorption seen in quasi-stellar object (QSO) spectra (Churchill & Le Brun 1998), while their presence in large numbers could be important to theories of galaxy formation and evolution.

Contemporary views as to the global significance of LSB galaxies are wide ranging, partly as a result of conflicting and usually indirect evidence, but mainly as a consequence of conflicting interpretation (Impey & Bothun 1997; Davies, Impey & Phillipps 1999).

Blind searches in the 21-cm neutral hydrogen line have long been considered an alternative to optical surveys for finding LSB disc galaxies (Disney 1976). The narrowness of the line means that cosmic expansion will discriminate between extragalactic and local hydrogen, so reducing the local background to the instrumental level beyond a redshift of a few hundred km s$^{-1}$. Fortunately, blind 21-cm surveys have until recently been severely limited by technical considerations, in particular by the tiny areas and small velocity ranges that could be covered to any depth in a practical time.

Recent technical advances, including high-sensitivity multibeam receivers and powerful correlators, have allowed much more ambitious blind surveys to be carried out. All-sky surveys of the southern hemisphere from Parkes (the H I Deep All-Sky Survey, HIJASS) and of the northern hemisphere from Jodrell Bank (the H I Jodrell All-Sky Survey, HIJASS) are currently being completed. These have integration times of 450 and 350 s per beam, respectively (Staveley-Smith et al. 1996; Lang et al. 2003), giving very similar sensitivities to sources smaller than the beam. To supplement these shallow surveys we have carried out the much deeper HIDEEP survey (9000 s beam$^{-1}$) of a small area of sky ($4 \times 8$ deg$^2$) out to a velocity of 12 700 km s$^{-1}$.

The main motive for HIDEEP was to reach previously inaccessible surface-brightness levels. In general one might expect surface brightness to be correlated with H I column density. Indeed, if one assumes that gas and starlight are distributed over proportionate areas it is easy to show that (Appendix A)

$$N_{HI} \approx 10^{20.1} \left( \frac{M_{HI}}{L_B} \right) 10^{0.4(B-M_B)}$$

(1)

a relationship tabulated in Table 1. To reach LSB galaxies ($\mu_0 \geq 24$ $B$ mag arcsec$^{-2}$) that have ‘normal’ amounts of H I ($e.g.$ $M_{HI}/L_B = 0.3$) requires an H I survey reaching down to $N_{HI} \leq 3 \times 10^{19}$ cm$^{-2}$, while to reach really low surface-brightness objects with $\mu_0 \geq 26.5$ $B$ mag arcsec$^{-2}$ requires an H I survey 10 times more sensitive. Unfortunately, such low column densities can be reached only by very long integrations, irrespective of dish size (as diffraction-limited beams decrease in angular area exactly in inverse proportion to the dish area). In single-dish surveys, the detection of sources smaller than the beam will depend only on the mass of H I ($M_{HI}$) per velocity channel in the beam, and their H I column densities ($N_{HI}$, measured in cm$^{-2}$) will be irrelevant. As we shall demonstrate (Section 3 below) our survey is peak-flux-limited so that, for detection

$$S_{\text{peak}} > n\sigma,$$

(2)

where $S_{\text{peak}}$ is the peak flux and $\sigma$ is the noise per channel per beam. As $S_{\text{peak}} \propto (M_{HI}/d^2 \Delta V)$ and $\sigma \propto 1/(D^2 t^{1/2})$, where $D$ is the diameter of the dish, $d$ is the distance to the source and $t_{\text{int}}$ is the integration time, this can be rewritten as

$$\frac{1}{d^2} \left( \frac{M_{HI}}{\Delta V} \right) D^2 t^{1/2} > k_1,$$

(3)

where $k_1$ is a constant. Thus the maximum distance for source detection will be

$$d_{\text{max}} \propto \left[ \left( \frac{M_{HI}}{\Delta V} \right) D^2 t^{1/2} \right]^{1/2},$$

(4)

and the maximum volume in which such sources ($M_{HI}, \Delta V$) will be detected is

$$V_{\text{max}} = \frac{\Omega_t}{3} N_{HI} d_{\text{max}}^3 = \frac{\Omega_t}{3} \left( \frac{T}{t} \right) d_{\text{max}}^3$$

(5)

(where $\Omega_t$ is the beam size in sterads, $N_{HI}$ is the total number of beams in the survey and $T$ is the total duration of the survey).

Thus the volume surveyed (and hence the number of detections) per unit time is

$$\frac{V_{\text{max}}}{T} \propto \frac{1}{t} t^{3/4} \propto t^{-1/4}$$

(6)

i.e. short integration times per beam are favoured in order to find the most sources.

However, short integration times imply that sources will only be detected nearby, and if they are too close they will overfill the beam, reducing the amount of H I within it. In these circumstances, equation (3) must be adapted to

$$\frac{1}{d^2} \left( \frac{d^2 \Omega_t N_{HI}}{\Delta V} \right) D^2 t^{1/2} > k_2,$$

(7)

where $N_{HI}$ is the column density in cm$^{-2}$ and $k_2$ is a constant. As $\Omega_t = (\lambda/D)^2$

$$\frac{N_{HI}}{\Delta V} > \frac{k}{\sqrt{t}},$$

(8)

where $k$ is a constant. Equation (8) is independent of $D$, dish diameter and is a mandatory requirement for detection because a source that cannot be detected when it fills the beam certainly cannot be detected when it does not. In other words, short integration-time surveys are only sensitive to high column-density sources, irrespective of dish size, a limitation which is seldom acknowledged (e.g. Zwaan et al. 1997). (See Appendix B for a full derivation of equation 8.)

We now show that the volume in which a galaxy can be detected only depends on its peak flux, and is independent of the actual column density, as long as the peak flux is higher than the survey limit.

First, let us consider the case of a galaxy with mass $M_{HI}$, and velocity width $\Delta V$, which just fills the beam (case a in Fig. 1). We will also assume that it is at the peak flux limit $S$ of the survey. As
that for this galaxy peak column density will also have a peak column density is directly proportional to the limiting peak column density. At a distance \(d^\prime > d\). The galaxy does not fill the beam, but the low column density yields a peak flux \(S\) lower than the survey limit. This galaxy will not be detected.

The latter limit only depends on the flux per velocity channel we find that for this galaxy

\[
M_{\text{HI}} \propto S(\Delta V) d^2 \propto N_{\text{HI}, \text{gal}}^2 \propto N_{\text{HI}, d^2/\Omega_{\text{gal}}}^2
\]

or

\[
S\Delta V \propto N_{\text{HI}, \Delta \Omega_{\text{gal}}}
\]

where in this case \(\Delta \Omega_{\text{gal}} = \Delta \Omega_{\text{beam}}\). As our survey is peak-flux-limited and \(\Delta \Omega_{\text{beam}}\) is constant, we find that, at fixed \(\Delta V\), the limiting column density is directly proportional to the limiting peak flux. In other words, a galaxy with a column density lower than the limiting column density will also have a peak flux lower than the limiting peak flux, and can thus never be detected.

A more compact galaxy with the same \((M_{\text{HI}}, \Delta V)\) at the same distance must necessarily have a higher column density (case b in Fig. 1). This increase in column density compensates for the beam dilution factor \(r_{\text{gal}}/r_{\text{beam}} = \Delta \Omega_{\text{gal}}/\Delta \Omega_{\text{beam}}\), and the galaxy will still be detected, as its peak flux \(S\) is higher than the survey limit.

In contrast, if we take the galaxy from our original example (which just fills the beam at distance \(d\)) and put it at a larger distance \(d^\prime\) (case c in Fig. 1), the peak flux drops by a factor \((d'/d)^2\) and will not meet the survey limit.

The detectability of a galaxy is thus independent of its column density, provided that its peak flux is higher than the survey limit. A galaxy filling the beam at the peak flux survey limit will have the lowest detectable column density. At a fixed \((M_{\text{HI}}, \Delta V)\), galaxies with higher column densities (necessarily) do not fill the beam, but will be detected over the same volume, as they will exhibit identical peak fluxes. Similar galaxies at larger distances will not be detected, independent of column density, as they will drop below the peak flux limit.

Table 2 demonstrates this for galaxies of different masses and column densities. The \(10^{18}\) cm\(^{-2}\) galaxy is below the column-density limit and will never be detected in HIDEEP. All the other galaxies are above the column-density limit and are therefore detected out to the distances set by their peak fluxes. The volume over which a galaxy above the column-density limit will be detected is determined solely by the peak flux of the galaxy.

In summary, 21-cm surveys have two constraints: (a) a peak-flux limit given by equation (3) in which dish size \((D)\) is a distinct advantage and (b) a surface-density limit where dish size is irrelevant, but in which integration time per beam is all important. In a search for high column-density \(N_{\text{HI}}\) objects, short integration times per beam are favoured; in a search for low column-density (and therefore low surface-brightness) objects, long integrations are mandatory. (An alternative way of looking at this is to note that larger dishes project the same system noise on to smaller areas of sky, because their diffraction-limited beams are smaller, and so have to contend with higher apparent sky noise.) Thus, HIDEEP and HIPASS are complementary: HIPASS with its relatively short integration time per beam (450 s) picks up large numbers of high surface-density sources but is insensitive to objects below \(1.6 \times 10^{19}\) cm\(^{-2}\) \((\Delta V = 200\) km s\(^{-1}\)) while HIDEEP with its very long integration time per beam (9000 s) is the first blind survey (see Table 3) capable of reaching much lower surface-density \(N_{\text{HI}}\), and hence surface-brightness, limits.

Before the advent of the multibeam system at Parkes it was neither profitable nor practical to make the very long integrations required to reach low column density. Thus the limits quoted in such surveys for the total amount of cosmic H\,I referred only to high column-density clouds and galaxies, though this was rarely acknowledged. Their integration times per beam were mostly far too short to detect the lower surface-density features. HIDEEP (see Appendix B) should and indeed does reach

\[
N_{\text{HI}} \geq 2.1 \times 10^{16} \Delta V \simeq 4 \times 10^{18} \text{ cm}^{-2}
\]

for a typical galaxy with a velocity width of 200 km s\(^{-1}\).

In principle, therefore, we should be able to reach galaxies with lower surface brightnesses than any detectable before either in H\,I or in the optical (see Table 1).

The H\,I survey is complemented by deep optical observations, reaching an isophotal level of 26.5 mag arcsec\(^{-2}\) in the R band, covering three-quarters of the survey region. For our analysis, we assume a value of \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) throughout.

### 2 Previous 21-cm Blind Surveys

Despite technical difficulties, blind surveys have been carried out, often using special techniques (see Table 3 for details). For instance, Shostak (1977) re-examined the signals in the ‘off-beams’ of an NRAO 300-ft survey, where the ‘on-beams’ were pointed at bright, optically selected galaxies. Latterly, Zwaan et al. (1997) and Schneider, Spitzak & Rosenberg (1998) have used the Arecibo radio telescope to carry out deep surveys. The results of such blind surveys have generally proved negative in the sense that very few previously uncatalogued galaxies or intergalactic gas clouds (IGCs) were detected.

| \(N_{\text{HI}}\) cm\(^{-2}\) | 10\(^{13}\) M\(_{\odot}\) | 10\(^{16}\) M\(_{\odot}\) | 10\(^{19}\) M\(_{\odot}\) | 10\(^{22}\) M\(_{\odot}\) |
|-----------------|----------------|----------------|----------------|----------------|
| 10\(^{18}\) cm\(^{-2}\) | 0 | 0 | 0 | 0 |
| 10\(^{19}\) cm\(^{-2}\) | 0.22 | 6.9 | 220 | 6900 |
| 10\(^{20}\) cm\(^{-2}\) | 0.22 | 6.9 | 220 | 6900 |
| 10\(^{21}\) cm\(^{-2}\) | 0.22 | 6.9 | 220 | 6900 |
However, as shown in Table 3, such surveys did not have sufficient sensitivity to low column density ($N_{\text{HI}}$) gas to actually detect such objects. Quite apart from the theoretical arguments leading to equation (8), the column-density sensitivity of any survey can be estimated retrospectively from its sensitivity to unresolved sources because (see Appendix C)

$$N_{\text{HI}}^{\text{min}}(\Delta V) = 4.5 \times 10^{20} \left( \frac{F_{\text{gal}}}{\Delta V \delta \theta^2} \right)_{\text{min}} \Delta V,$$

(12)

where $F_{\text{gal}}$ and $\Delta V_{\text{gal}}$ are the integrated flux (in Jy km s$^{-1}$) and the velocity width (in km s$^{-1}$) of the source in the survey with the lowest value of $F_{\text{HI}}/\Delta V$ and $\delta \theta$ is the source size in arcmin. When considering large LSB galaxies which could fill the beam, we set $\delta \theta$ equal to the beam FWHM to find the sensitivity to such systems. That the left-hand side of equation (12) is independent of dish size can be seen from the right-hand side as both the minimum flux (top) and the beam size (bottom) are inversely proportional to the dish area.

An examination of the various survey source limits shows excellent agreement between the column density as calculated according to Appendix C and separately from applying equation (12) to the various source lists. For instance, if we look at the deep drift-scan survey carried out by Zwaan et al. (1997), the Arecibo HI Strip Survey (AHISS), and examine those sources that lie within its main beam, we can use these to calculate the column-density limit of this survey for a typical velocity width of 200 km s$^{-1}$. We find that this limit is

$$N_{\text{HI}}(\text{AHISS}) \gtrsim 3.5 \times 10^{19}$$

(13)
i.e. $N_{\text{HI}}^{\text{min}}(\text{AHISS}) \gtrsim 10^{20.6}$ cm$^{-2}$ – almost precisely the minimum value found by the VLA follow-up observations. In other words, the AHISS survey was a shallow survey capable only of picking up sources down to a few times $10^{19}$ cm$^{-2}$ with a velocity width of $\Delta V = 200$ km s$^{-1}$. The AHISS results do not, therefore, rule out the presence of a population of low column-density galaxies. It should be noted that the 5$\sigma$ column-density sensitivity for AHISS given in Table 3 is substantially lower than that found in equation (13). This is consistent with the finding of Schneider et al. (1998) that the limit for AHISS is well above 5$\sigma$.

The other recent deep Arecibo survey, the Arecibo Slice (Schneider et al. 1998; Spitzak & Schneider 1998) operated rather differently. Patches of sky about two beam diameters apart were followed for 60 s, and any sources tentatively picked up were then rescanned using a grid search. This meant that the sensitivity varied by a factor of $\approx \pm 4$ over the total 55 deg$^2$ searched. The median flux of the sources detected over the velocity range 100–8340 km s$^{-1}$ was 2.69 Jy km s$^{-1}$ as against the median value for HIDEEP of 1.96 Jy km s$^{-1}$. Because of the short 60-s integration time, the sensitivity to low-column-density sources was poorer than AHISS. Nevertheless, there were interesting results. Only half the galaxies detected were in any optical catalogue and about a third were LSB galaxies. The galaxies have much lower bulge-to-disc ratios than found in optically selected samples. The median $M_{\text{HI}}/L_B$ of the survey was 0.89 $M_{\odot}/L_{\odot}$ and the galaxies with larger $M_{\text{HI}}/L_B$ ratios had lower surface brightnesses.

Henning’s (1992, 1995) survey with the Green Bank 300-ft telescope was largely behind the galactic plane and therefore not comparable with HIDEEP. The Arecibo Dual Beam Survey (ADBS; Rosenberg & Schneider 2000, 2002) covered a larger area of sky than the other surveys but to a much shallower depth, and so could not set any limits to the population of low column-density galaxies.

Although blind 21-cm surveys are, in principle, the ideal way of circumventing optical selection effects and looking for LSB galaxies and IGCs, the weakness of the 21-cm signal and the system noise make it very difficult to find sources unless they have high column densities. Only very long integrations are capable of reaching low column-density limits, and possibly finding objects of lower surface brightness than can be seen optically – thus the interest of HIDEEP.

### Table 3. Blind HI surveys.

| Telescope          | AHISS$^a$ | Arecibo Slice$^b$ | Shostak (1977) | Henning (1995) |
|--------------------|-----------|-------------------|----------------|----------------|
| Area (deg$^2$)     | 3.3 arcmin| 3.3 arcmin        | 10.8 arcmin    | 10.8 arcmin    |
| FWHM               | 3.3 arcmin| 3.3 arcmin        | 154           | 183           |
| $\sigma_{\text{HI}}$ limit ($M_{\odot} d_{\text{MCW}}^{-2}$) | $1.0 \times 10^5$ | $2.8 \times 10^5$ | $2.5-15 \times 10^6$ | $4.7 \times 10^5$ |
| $\sigma_{\text{HI}}$ limit (cm$^{-2}$) | $1.8 \times 10^{19}$ | $4.8 \times 10^{19}$ | $4.1-24 \times 10^{19}$ | $7.7 \times 10^{18}$ |

$^a$Zwaan et al. (1997).
$^b$Schneider et al. (1998).
$^c$Area within FWHM of beam.
$^d$For $\Delta V = 200$ km s$^{-1}$, peak-flux-limited.
We claim that the arguments summarized in equation (1) and Table 1 demonstrate that we should, for the first time at 21 cm, be capable of locating such objects. Even so, the limitations of all such blind H I surveys should constantly be borne in mind. Such surveys have lower sensitivity to broader-line sources (see below) and may, particularly at low column densities (<10^19 cm^-2), be severely affected by ionization and spin temperature effects (Section 4). H I surveys, therefore, can only set lower limits to the number of LSB galaxies and IGCs in the cosmos.

3 THE HIDEEP SURVEY

3.1 The H I data

HIDEEP was carried out in a region of Centaurus centred on α = 13°40′00″, δ = −30°00′00″ (J2000) with 1024 spectral channels covering −1280 to 12 700 km s^-1. As a result of the shape of the Parkes multibeam footprint, the survey has a sensitivity as good as or better than HIPASS over 6 × 10 deg^-2 with a uniform sensitivity over the central 4 × 8 deg^-2 area. This region lies in the supergalactic plane, 30° from the galactic plane. The HIDEEP volume includes the Cen A group (Banks et al. 1999) and the outer parts of the Centaurus cluster. The observations were carried out in the southern autumns of 1997, 1998, 1999 and 2000.

The data were processed using the standard multibeam reduction techniques, as described in detail by Barnes et al. (2001). Continuum sources were removed using LUTHER (Wright & Stewart 2003, in preparation). Once integrated, the data take the form of a cube with voxels (three-dimensional pixels) 4 × 4 arcmin^2 on a side and 13.2 km s^-1 deep. The half-power beamwidth is 15 arcmin and the data were smoothed in the velocity direction (to reduce ringing) as part of the reduction process, giving a velocity resolution of 18 km s^-1. The data in adjacent voxels are therefore not entirely independent.

The sky was Nyquist sampled 50 times and some 1800 separate samples contributed to the signal in each voxel. Median filtering of this large sample greatly reduces interference while the data were all taken at night to avoid solar radiation entering the beam sidelobes—a major source of noise during the day.

The final data cube can be examined in three planes: (α, δ), (δ, V) and (V, α), where V is the velocity direction. All three planes are used for finding and measuring sources. Fig. 2 shows a (δ, V) slice of the cube, showing the strong galactic signal at 0 km s^-1 as well as 12 other sources, including NGC 5236 (M 83) at 500 km s^-1 and GSC 7265 02190 at 11 875 km s^-1 (Willmer et al. 1999). Continuum sources have been removed and the nature of the remaining noise, against which sources must be found, can be seen. The ripple seen just below −34° Dec. is the residual of the strong continuum from the southern radio lobe of IC 4296. The increased noise at the edges of the cube is the result of poorer sampling in these regions.

Fig. 3 demonstrates the effectiveness of long integrations. We plot the median noise in mJy beam^-1 channel^-1 for integrations of 450 s beam^-1 (HIPASS), 5600 s beam^-1 (Minchin 2001) and 9000 s beam^-1 (HIDEEP). As can be seen it falls to 3.2 ± 0.3 mJy beam^-1 channel^-1 against time in accordance with the theoretical 1/√t^-0.5.

Fig. 4 shows that smoothing in the velocity plane is a much less effective way of reducing the noise. We have smoothed the data with a Hanning filter and removed every other channel from the smoothed cube in order to leave only the independent channels. This has been repeated to form cubes smoothed over 2, 4, 8, 16 and 32 channels. For white noise, the noise should fall as 1/√Nchan (where Nchan is the number of channels smoothed over), however, it can be seen that this is not the case for Nchan > 4. Beyond this the fall off is shallower than predicted by Poisson statistics—closer to Nchan^-0.3, although it is not well described by a power law.

3.2 Source finding

The HIDEEP cube was searched three times in an independent manner. Two different people searched through the cube by eye, inspecting every channel and noting down the sources found, and the
third search was carried out by an automated finding routine based on peak-flux detection and template fitting. This routine identified points higher than 4.5σ on a Hanning-smoothed cube and fitted Gaussian templates with a large range of widths at these points, demanding a correlation of better than 0.75. The three lists given by these searches were then compared and any sources found two or more times were accepted. The remaining disputed sources were examined by a third member of the team for a final decision. This team member had not previously searched the data cube.

This gave us a final list of 173 sources, all of which have been judged as real by at least two members of the team acting independently. Accurate positions for all the sources were found by forming zeroth-moment maps around their positions and velocities and fitting Gaussians to these maps. This gives a positional accuracy, as judged from those sources that can be securely identified with optical galaxies, of around 2 arcmin (see Fig. 9 later). The HI parameters of the galaxies were measured using the MBSPECT routine in MIRIAD, which provides measures of the velocity width, the noise in the spectrum and the peak flux of the source as well as robust estimates of the integrated flux and systemic velocity.

3.3 Completeness of HIDEEP

The form of the selection present in the HIDEEP survey has been analysed by plotting the integrated flux of the galaxies against their velocity width (Fig. 5). For a survey limited solely by the total flux of the galaxies, the selection limit on this graph would be a horizontal line. If the best possible real-world selection was made, i.e. selection purely by signal-to-noise (S/N) ratio using optimal smoothing in the velocity plane, then the selection limit would be a line with a slope of 0.5 on a log–log plot (assuming S/N \( \propto 1/\sqrt{\Delta V} \)), which is not strictly true as shown in Fig. 4, shown here as a dashed line. The solid line on the graph shows a selection limit based on peak flux (\( F_{\text{HI}} \propto \Delta V_{20} \)); only 16 of the 173 sources fall below this line and only eight of these are below by more than 1σ. Sources appear to fall further below the line at the low-flux, low-velocity width end, but this is probably due to the larger errors in this region. The peak-flux selection limit is shown in Fig. 6. It can be seen that this explains well the selection limit of the survey.

It can also be seen in both graphs that there is a paucity of galaxies narrower than approximately four channel widths (52.8 km s\(^{-1}\)). This further selection effect, thought to be due to galaxies narrower than this being indistinguishable from interference, is investigated in detail by Lang et al. (2003).
The HIDEEP Survey

To identify LSB galaxies it was necessary to obtain very deep optical data to compare with the radio data. Accordingly eight 1-h 6 × 6 deg² R-band Tech-Pan films were exposed at the UK Schmidt Telescope, centred on 13h39m50s, −30°00′12″ (J2000). These were digitized, linearized and stacked using the SuperCOSMOS machine at the UK Astronomical Technology Centre in Edinburgh (Hambly et al. 2001). The final image was then calibrated using the magnitudes of unsaturated ESO-LV (Lauberts & Valentijn 1989) galaxies within the region, which yields a calibration accuracy of approximately 0.2 mag. The Tech-Pan films used go 1 mag deeper than the IIIaF plates previously used at the UKST (Parker & Malin 1999) and the digital stacking gives a further gain of over a magnitude compared with a single exposure (Schwartzenberg et al. 1996). The limiting surface brightness reached for small objects within the image is then 26.5 $R$ mag arcsec⁻², equivalent to between 27 and 28 $B$ mag arcsec⁻².

Within the overlap region between the radio and optical images we find 96 HI sources that have been uniquely identified with optical counterparts.

Sources have been identified with galaxies on the optical image, first on the basis of positional coincidences. Multibeam survey positions are generally accurate to 2 arcmin (Koribalski et al. 2003), but this can be checked for the 65 optical counterparts that have previously published optical velocities or for which we have our own optical spectroscopy or 21-cm interferometry data. A comparison can be made between the (radio–optical) offsets of these firm detections with the remainder (Fig. 9). A Kolmogorov–Smirnov test confirms that there is no significant difference between the distributions, implying that the purely positional coincidences can generally be trusted. There may still be one or two incorrect identifications, but the tail of offsets out to 6.5 arcmin probably reflects the positional accuracy of the HIDEEP survey.

In the overlap area 59 per cent of the sources are identified with previously catalogued galaxies with matching redshifts, 24 per cent

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**Figure 7.** Completeness of the HIDEEP survey: source count against peak flux ($S_{\text{peak}}$). The histogram shows numbers found in each bin of peak flux, the curve represents $N(S_{\text{peak}}) \propto S_{\text{peak}}^{-5/2}$ as expected for a flux-limited survey.

**Figure 8.** Completeness of the HIDEEP survey: log–log plot of source count against peak flux. The solid line has a slope of $-3/2$, as expected for a flux-limited survey.

**Figure 9.** Comparison between the cumulative distributions of offsets for the firm identifications (solid line) and the less certain counterparts (dashed line).
Figure 10. Number of galaxies found in each surface-brightness bin. The solid line shows the distribution of observed surface brightnesses, the dashed line shows the distribution of surface brightnesses after correction for galactic absorption, cosmological dimming, and inclination.

with previously catalogued galaxies without redshifts and 17 per cent are previously uncatalogued galaxies. It appears that there are no intergalactic gas clouds unassociated with optical counterparts: all of those galaxies that have not been uniquely associated with a counterpart have more than one plausible candidate.

We have measured effective radii and surface brightnesses by fitting to the surface-brightness profiles of the optical sources using the ELLIPSE routine in IRAF. The total magnitudes used were determined by SEXTRACTOR (Bertins & Arnouts 1996). The surface-brightness distribution (Fig. 10) is much broader than one finds in optically selected samples. A Kolmogorov–Smirnov test of our distribution and the surface-brightness distribution of the ESO-LV shows that the hypothesis that both are drawn from the same parent population has a significance of less than 1 per cent — this is due to the larger number of LSB galaxies seen in the HIDEEP sample. This confirms that H I surveys do, as expected, avoid some of the surface-brightness selection effects present in optical surveys. A fuller description and analysis of the optical properties will be given in a second paper (Minchin et al. 2003, in preparation).

3.5 Internal H I correlations

A correlation between H I mass and observed velocity width of the form $\Delta V \propto M_{\text{HI}}$ (where $\Delta V$ is the velocity width uncorrected for inclination) is expected in the HIDEEP data as it has been seen in optically selected samples (e.g. Briggs & Rao 1993) and as it would be the consequence of the H I Tully–Fisher relationship.

That such a relationship can be seen in the HIDEEP data is shown in Fig. 11. The solid lines shown here is for the best fit of $\Delta V = 0.42^{+0.30}_{-0.17} M_{\text{HI}}^{0.282\pm0.025}$. The dashed line shows $\Delta V = 0.15 M_{\text{HI}}^{1/3}$ as found by Briggs & Rao (1993). The best-fitting slope found for the HIDEEP data is 2σ shallower than this, however, this may be due to the selection against narrow velocity-width galaxies seen earlier. We cannot, therefore, conclusively say that our sample shows a different relationship from that found by Briggs & Rao.

It is also expected that there will be a relationship between the peak flux and the value of $F_{\text{HI}}/\Delta V_{20}$ — the peak flux of a top-hat function with a width of 20 per cent of the width of the source and containing the same total flux. This relationship is important for calculated H I mass limits in a peak-flux-limited survey, as it is necessary for relating the peak-flux limit to the integrated flux ($F_{\text{HI}}$) on which the H I mass depends.

However, as this relationship depends on the profile shape it may well vary with H I mass. This is investigated in Fig. 12. This figure

Figure 11. H I mass–velocity width relationship for HIDEEP sources. The best fit to the HIDEEP data ($\Delta V = 0.42^{+0.30}_{-0.17} M_{\text{HI}}^{0.282\pm0.025}$) is shown by a solid line, while the fit of $\Delta V = 0.15 M_{\text{HI}}^{1/3}$ (Briggs & Rao 1993) is shown as a dashed line.

Figure 12. Comparison of the ratio $S_{\text{peak}} / (8 \mu \text{K} \Delta V)$ with $M_{\text{HI}}$. The slope of the best fit to this data is indistinguishable from zero, we therefore use the median value, $1.7 \pm 0.3$ to describe the ratio across all H I masses.
shows that there is no dependence of the ratio $S_{\text{peak}} / M_{\text{H}i}$ on $M_{\text{H}i}$; the slope of a fit to the points is statistically indistinguishable from zero. We therefore take the ratio to be a single number for all $M_{\text{H}i}$ masses, using the median value $1.7 \pm 0.3$. This value was used to calculate the 3σ peak-flux limit in Fig. 5.

The $M_{\text{H}i}$ mass distribution of the HIDEEP sources is shown in Fig. 13. This shows both the distribution of all the sources in HIDEEP (solid line), the distribution if the Centaurus A group galaxies are ignored (dashed line) and the distribution of galaxies included in the optical sample (dotted line). It can be seen that most of the low-mass galaxies are, unsurprisingly, in the Centaurus A group but we find only one high-mass galaxy (Messier 83). There are 22 hydrogen giants with $M_{\text{H}i} > 10^{10} M_\odot$, but only NGC 5291 has a mass greater than $3 \times 10^{10} M_\odot$. There are no galaxies detected outside the range $10^9 < M_{\text{H}i} < 10^{11} M_\odot$. The optical sample is similar in shape to the full sample, but contains fewer sources. This is mainly because it covers a smaller area. Some sources have also been omitted as a unique optical counterpart could not be identified.

### 3.6 Sensitivity and comparisons with previous surveys

Using the completeness limits and relationships found in the $M_{\text{H}i}$ data, we can calculate the sensitivity limit of the HIDEEP survey to galaxies of different masses and different column densities. The mass (in solar masses) is related to the integrated flux by the equation

$$ M_{\text{H}i} = 2.356 \times 10^5 F_{\text{H}i} d_{\text{Mpc}}^2 $$

(14)

(for $F_{\text{H}i}$ in Jy km s$^{-1}$) and the total flux is related to the peak flux and the velocity width (Fig. 12) by

$$ S_{\text{peak}} = (1.7 \pm 0.3) \times \frac{F_{\text{H}i}}{\Delta V_{20}}. $$

(15)

This allows the mass to be related to the peak flux as

$$ M_{\text{H}i} \simeq 1.386 \times 10^5 S_{\text{peak}} \Delta V_{20} d_{\text{Mpc}}^2. $$

(16)

However, the velocity width is a function of the mass, $\Delta V \simeq 0.15 M_{\text{H}i}^{1/3}$ (although with a large scatter). If we use the relationship found by Briggs & Rao (1993) then

$$ M_{\text{H}i} \simeq (0.15 \times 1.386 \times 10^3 S_{\text{peak}} d_{\text{Mpc}}^2)^{3/2}, $$

(17)

which gives

$$ M_{\text{H}i} \simeq 3.0 \times 10^6 S_{\text{peak}}^3 d_{\text{Mpc}}^3 $$

(18)

and putting in the completeness limit of $S_{\text{peak}} = 0.018$ Jy gives

$$ M_{\text{H}i} \simeq 7.24 \times 10^3 d_{\text{Mpc}}^3. $$

(19)

which is the sensitivity limit for sources of different masses at different distances. Since the relationship between velocity width and mass has a large scatter this is not the absolute detection limit: sources narrower than predicted by this relationship will be seen further out, and sources wider than predicted will be found over a smaller volume. However, it does indicate the distance to which most sources of a given mass will be seen.

The relationship between mass and velocity width suggests the possibility of a selection effect in H$\text{I}$ surveys that appears to have been neglected in many previous surveys: that of a minimum believable velocity width. Below a certain mass, the velocity widths of many of the galaxies will be smaller than the minimum believable velocity width of the survey – the width at which a peak in the data is recognized to be a galaxy rather than a noise peak – and will not be catalogued. A fuller analysis of this effect, using data from the H$\text{I}$ Jodrell All-sky Survey, is given in Lang et al. (2003).

Examination of the HIDEEP data shows the minimum believable velocity width to be around four channels wide for $\Delta V_{20}$ or 52.8 km s$^{-1}$. This selection effect means that detecting large numbers of low-mass galaxies will require not only sensitivity but also narrow channel widths. However, this effect could remove at most $\sim 40$ per cent of $10^{10} M_\odot$ galaxies here. If the thermal broadening of the H$\text{I}$ is also taken into account, this percentage will fall. It is therefore unlikely that this will significantly change the shape of H$\text{I}$ mass functions down to their current mass limits. For HIDEEP, the distance at which galaxies that would be above the mass limit will fall below the minimum believable velocity-width limit is about 18 Mpc.

Fig. 14 compares the H$\text{I}$ mass sensitivity of three surveys: HIDEEP, the HIPASS Bright Galaxy Catalogue (Koribalski et al. 2003, BGC) and the Arecibo H$\text{I}$ Strip Survey (AHISS). A minimum believable velocity width of four channels has been applied to all of these surveys, although galaxies narrower than this can be seen if they have high peak signal-to-noise ratios. This will apply particularly to the HIPASS BGC, where the peak-flux cut-off of 116 mJy is more than 8σ. For AHISS a limit of 5.25 mJy, or seven times the stated noise value of 0.75 mJy per channel, was adopted. This appears consistent with an analysis of the fluxes and velocity widths from Zwaan (2000) and with the analysis of Schneider et al. (1998), who concluded that the AHISS survey was limited at 7σ due to the method of confirming sources. Only the primary beam area was used in calculating the volume covered by AHISS.

Having estimated the sensitivity to sources in the mass-limited regime, we can also estimate the sensitivity to sources in the column-density-limited regime. Column-density sensitivity has often been presented, in a similar manner to optical surface brightness, as not having a dependence on distance. However, the relationship between $\Delta V$ and $M_{\text{H}i}$, and the dependence of column-density sensitivity of $\Delta V$ (see equation 12) means that this is not the case for single-dish surveys – the tendency of higher mass sources to have larger velocity
widths means that they will: (i) be seen to greater distances due to their higher mass and (ii) will have a higher column-density limit due to their larger velocity width.

The column density of a source filling the beam (in $M_\odot\text{pc}^{-2}$) is given by

$$N_{\text{HI}} = \frac{M_{\text{HI}}}{\pi \theta^2 d_{\text{pc}}^2} M_\odot \text{pc}^{-2},$$

(20)

where $\theta$ is the HWHM of the telescope beam in radians and $d_{\text{pc}}$ is the distance of the source in parsecs. It can easily be seen that $N_{\text{HI}}$ is only independent of distance if the sensitivity of the telescope to $M_{\text{HI}}$ goes as $d^2$. This would only be the case if galaxies at all different HI masses had the same velocity width or if the survey was limited by integrated flux – neither of which are likely. There must, therefore, be a distance dependence for column-density sensitivity to average galaxies that follow the relationship between $M_{\text{HI}}$ and $\Delta V$.

Putting in the $M_{\text{HI}}$ sensitivity from equation (19) and the beam size of Parkes (15 arcmin) gives a column-density sensitivity for HIDEEP of

$$N_{\text{HI}} \simeq 6.1 \times 10^{16} d_{\text{pc}} \text{cm}^{-2}.$$  

(21)

Again, this will be affected by the minimum believable velocity-width limit. Column-density limits for the three surveys (HIDEEP, HIPASS BGC and AHISS) are given in Fig. 15, where it can be seen that HIDEEP has a considerable advantage.

Fig. 16 shows the region of $M_{\text{HI}}$–$N_{\text{HI}}$ space in which each survey is sensitive. HIDEEP extends the region of $M_{\text{HI}}$–$N_{\text{HI}}$ space explored. For instance, neither the HIPASS BGC or AHISS would find giant LSB galaxies unless they had very high ($M_{\text{HI}}/L_B$)s or very low velocity widths.

### 3.7 H I properties

The H I properties of a sample of HIDEEP sources are given in Table 4 (full table available on-line). Column 1 gives the HIDEEP identification for the source. Columns 2 and 3 give the right ascension and declination from fitting to the zeroth-moment map. Columns 4–6 give the noise as measured on the part of the spectrum not containing signal ($\sigma$), the integrated flux (zeroth-moment, $F_{\text{HI}}$) and the peak flux ($S_{\text{peak}}$), all as measured by MBSPect. Columns 7 and 8 give the systemic heliocentric velocity (first-moment, $V_0$) and the velocity width at 20 per cent of the peak flux ($\Delta V_{20}$), measured by MBSPect.

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in the radio-velocity frame \((c\Delta v/v)\) and converted to \(cz\). Column 9 gives the distance in Mpc calculated from the cosmic microwave background (CMB) rest-frame velocity of the sources, which is approximately \(V_{\text{SMC}} = V_o + 278 \pm 8 \text{ km s}^{-1}\) for the HIDEEP region (the exact correction varies across the field). This does not include any correction for bulk motions (Virgo-centric infall, etc.) nor does it include assigning sources beyond the Centaurus A group to clusters and assigning a single distance to that cluster. Galaxies at less than 1000 km s\(^{-1}\) have been assigned to the Centaurus A group at an assumed distance of 3.5 Mpc. Column 10 gives the \(H_\text{i}\) mass calculated from \(F_{\text{HI}}\) from column 5 and the distance from column 9 using the standard equation \(M_{\text{HI}} = 2.356 \times 10^8 F_{\text{HI}} d^2_{\text{Mpc}} M_{\odot}\), where \(F_{\text{HI}}\) in Jy km s\(^{-1}\).

### 3.8 Large-scale structure

The HIDEEP survey region lies in the supergalactic plane and there is, therefore, much large-scale structure in the survey volume. This can be seen in Fig. 17. In particular, the Centaurus A group, the Virgo Southern Extension and the Centaurus Cluster can be seen. Near the end of the bandpass a number of Abell clusters are found, and more lie beyond the outer velocity edge of our survey.

Fig. 18 shows that there is little correlation between the distribution of previously catalogue galaxies with redshifts above 10 000 km s\(^{-1}\) and the distribution of the HIDEEP sources in this velocity range. Only the Abell 3562 cluster appears to have a significant number of \(H_\text{i}\) detections and the \(H_\text{i}\) sources also appear to populate the void at the northwest of the region. It is possible that the lack of correlation is due to the targeting of optical redshift surveys towards the Abell clusters, thus increasing the number of redshifts in those regions out of proportion to their density. While Abell 3571 and 1736 are both centred inside the HIDEEP volume, at 11 500 and 10 500 km s\(^{-1}\), respectively, Abell 3558 and 3562 are both centred beyond 14 000 km s\(^{-1}\) (Abell, Corwin & Olowin 1989; Quintana & de Souza 1993). Only the low-velocity tails of these two clusters can be seen.

### 3.9 Follow-up observations

Follow up observations of some sources were carried out at 21 cm using the Australia Telescope Compact Array (ATCA) and optically using the Double Beam Spectrograph on the ANU 2.3-m telescope at Siding Spring Observatory. The ATCA observations were carried out in the 375-m configuration in 1999 November and 2000 January and gave us high-resolution 21-cm maps of the targeted sources in order to accurately determine their positions. 10 out of 14 sources were detected. As the column-density sensitivity limit for these observations was around \(10^{21} \text{ cm}^{-2}\), substantially higher than the limit for the HIDEEP survey, the non-detections do not tell us anything concerning our survey limits.

Optical spectroscopy has enabled us to positively identify ESO 509-G075 as the counterpart of HIDEEP J1335-2730 (which was undetected with ATCA) despite a previous optical redshift (Quintana et al. 1995) placing it at twice the velocity of the \(H_\text{i}\) source and allowed us to separate Abell 3558\,[MGP94]4312 and 4317, which...
were too close together to be separated by ATCA, identifying 4317 as the optical counterpart of HIDEEP J1334-3223.

4 INFERRED $H_I$ COLUMN DENSITIES

We have not yet obtained high-resolution $H_I$ images of most of our sources so we do not know either their $H_I$ radii or column densities. We therefore calculate an inferred column density ($N_H$) from the $H_I$ mass and the optical (effective) radius. Because of our long integration time and low noise, we could in principle reach column densities between one and two orders of magnitude deeper than previous blind surveys (Section 2). It is of interest to look for evidence, however, indirect, as to whether this previously unexplored parameter space is populated.

Salpeter & Hoffman (1996) found that $r_{H_I} = (2.34 \pm 0.14) \times r_{B25}$ for an optically selected sample of galaxies. Obviously $r_{B25}$ is not a good measure for the $H_I$ radii of LSB galaxies, which may not have a $B_{25}$ isophote. However, the effective radius ($r_e$) provides a model and surface-brightness-independent measure of the optical size of galaxies. In order to obtain a relationship between $r_e$ and $r_{H_I}$, it is necessary to assume a relationship between $r_{B25}$ and $r_e$. This obviously introduces some unavoidable model dependence into the analysis. As the relationship between $r_{H_I}$ and $r_{B25}$ is defined for HSB galaxies, we should define the relationship between $r_e$ and $r_{B25}$ for a similar sample. There is a further assumption here that the proportionality between $r_e$ and $r_{H_I}$ found for these HSB galaxies will remain constant as we go to lower surface brightnesses. This may not be the case, and would introduce systematic errors into our analysis, however, $r_e$ is certainly a better choice than $r_{B25}$ for looking at LSB galaxies. We use the relationship for disc galaxies in the ESO-LV catalogue (Lauberts & Valentijn 1989) that $r_{B25} = (2.15 \pm 0.67) \times r_e$. This then gives us

$$r_{H_I} = (5.03 \pm 1.59) \times r_e.$$  

(22)

From this we can calculate the inferred mean column density $N_{H_I}$ as

$$N_{H_I} = 10^{20.1} \frac{M_{H_I}}{\pi R_{H_I}^2} \text{ cm}^{-2},$$  

(23)

where $R_{H_I}$ is the radius in parsecs, calculated from $r_{H_I}$ using the distance to the source.

Fig. 19 shows these inferred column densities plotted against their velocity widths. Above the survey limit (dashed line), the volume sampled depends only on $H_I$ mass (or, more precisely, on peak flux) and not on column density, as shown earlier in Fig. 1. If low column-density galaxies were common, we would expect to see galaxies at all column densities in this plot. However, this is clearly not the case – there is a large gap between the lowest column-density galaxies found and our sensitivity limit.

That this gap is real and not an artefact of our method is shown in Fig. 20. Here the sample has been split into four sections, according to the beam-filling factor ($\Delta \Omega / \Omega_{beam}$) of the sources, and the column-density limits calculated with this included. The top left-hand panel shows that we are detecting galaxies up to the column density limit of the survey for this range in beam filling factors. These are galaxies with small beam-filling factors, and we can see...
The HIDEEP Survey

**Figure 19.** Inferred column densities of HIDEEP sources against velocity widths. The limit shown is for the 18-mJy completeness limit for HIDEEP and sources filling the beam.

**Figure 20.** Inferred column densities of HIDEEP sources with different beam filling factors against velocity widths. The limits shown are for the 18-mJy completeness limit, the dotted line indicating the limit for the lower filling factor and the solid line the limit for the higher filling factor in each subgraph.

that the inferred column density limits for these galaxies are quite high (cf. equation B6). The top right-hand panel shows the limits for galaxies with slightly larger beam filling factors. Galaxies are detected with column densities close to the survey limit for this range in beam filling factors, but we can see that they do not approach the limit as closely as in the previous panel. This is an indication that in this sample galaxies with larger beam filling factors (and hence lower column densities; cf. Section 1) are rarer. This is confirmed by the two bottom panels. These show the limits for galaxies that come close to filling the beam (and thus have the lowest column densities). We see that despite the low limits, there are only two galaxies detected. This thus indicates an absence of low column density galaxies, despite their potential detectability.

Using the numbers of galaxies found within the overlap of the full-sensitivity H I survey and the optical survey, we calculate that, to 95 per cent confidence, low column-density galaxies make up less than 21 per cent of galaxies with H I masses between $10^6$ and $10^9$ M$_\odot$ (13 galaxies), less than 6 per cent between $10^9$ and $10^{10}$ M$_\odot$ (52 galaxies), and less than 19 per cent between $10^{10}$ and $10^{11}$ M$_\odot$ (14 galaxies).

If our estimate of $R_{HI}$ were out by more than a factor of 3, we would expect to see a lower limit to our column densities parallel to the plotted completeness limit. As the lower limit appears flat with respect to velocity width, it appears that there are indeed no large very low column-density galaxies in our sample. If such objects are present in the local Universe they must, therefore, be rare. We discuss possible reasons for this absence elsewhere (Disney & Minchin 2003).

The distribution of column densities appears to be the same at all surface brightnesses. A two-dimensional Kolmogorov–Smirnov test (Peacock 1983) shows that the observed distribution is indeed consistent with a distribution having the same column-density distribution as HIDEEP (Fig. 21) at every surface brightness. The distribution shown in Fig. 21, is well described by a Gaussian with log($N_{HI}$/cm$^{-2}$) = 20.65 ± 0.38. Fig. 22 shows the measured data that gives rise to a constant column density: a relationship between the effective radius and the HI flux. The dashed line on this graph is for a constant $N_{HI}$ of $10^{20.65}$ cm$^{-2}$, and it can be seen that this matches the data well. This apparent constancy of column density is unexpected; we would expect to see a fall-off towards lower surface brightness, as observed by de Blok, McGaugh & van der Hulst.

**Figure 21.** Distribution of inferred column densities of HIDEEP sources. The dashed line indicates a Gaussian with a mean of 20.65 and a scatter of 0.38. It can be seen that this is a fairly good description of the distribution.
(1996) for a sample of LSB galaxies observed with the Westerbork Synthesis Radio Telescope (WSRT).

Swaters et al. (2002) observed a number of optically selected galaxies with the WSRT, showing that the relationship between HI mass and diameter was much tighter when true HI diameters were used than when they were inferred from the optical radii. It is likely that much of the scatter in our relationship has been similarly introduced by our use of optical radii. Observations of the true HI diameters may well show a similar trend to that seen by de Blok et al.

In order to compare our sample with the literature, we have taken the LSB galaxy catalogue of Impey et al. (1996, ISIB96). This survey provides effective surface brightnesses and radii for all the galaxies found, across a wide range of surface brightness, and provides HI mass measurements for a subsample of 190 galaxies. We therefore calculate the column density from this data in exactly the same manner as for HIDEEP. The Impey et al. survey was carried out in the $B$ band, we therefore convert $\mu_e$ to $\mu_R$ using the average colour for disc galaxies from de Jong (1996), $B-R = 1.1$.

Fig. 23 shows the surface brightness–column-density distribution for both surveys. HIDEEP galaxies are indicated by solid triangles, ISIB96 galaxies by open circles. It can be seen that there is a clear trend in the ISIB96 data, which is similar to that seen by de Blok et al. (1996). The surface-brightness distribution of the ISIB96 galaxies is different from that of HIDEEP, due to the method in which the galaxies have been selected. In order to compare the surveys we have therefore resampled the ISIB96 data to give the same surface-brightness distribution (in 0.5 mag bins) as HIDEEP. This was carried out 10 times, and the subsamples compared with HIDEEP using the two-dimensional Kolmogorov–Smirnov test. Half of the subsamples were not significantly different at the 95 per cent level.

There are a number of systematics that could affect this comparison. Our measure of $r_e$ could be systematically too small towards lower surface brightnesses: this would lead to both $N_{\text{HI}}$ and $\mu_e$ being higher and so would act to destroy such a relationship between $N_{\text{HI}}$ and surface brightness. The colours will not be exactly the same for all the galaxies, introducing errors into the conversion of the

ISIB96 relationship to the $R$ band. The low column-density galaxies ($N_{\text{HI}} < 10^{20} \text{ cm}^{-2}$) in ISIB96 are generally large galaxies, with $r_{\text{eff}} > 20$ arcsec. Using our scaling between $r_{\text{HI}}$ and $r_{\text{eff}}$, this gives them HI sizes larger than the Arecibo beam. It is therefore likely that some of the hydrogen in these galaxies was missed in the pointed observations, leading to lower inferred column densities than is truly the case. We cannot, therefore, say that the HIDEEP data is inconsistent with ISIB96. If there is a relationship between surface brightness and $N_{\text{HI}}$, in our data, however, it is very weak indeed.

5 DISCUSSION, CONCLUSIONS AND FUTURE WORK

The existence of a large population of LSB galaxies could have a significant impact on several areas of astronomy, in particular on measurements of the luminosity and mass density of galaxies and on theories of galaxy formation and evolution. However, LSB objects are difficult to detect in the optical range since, by definition, they are hard to discriminate from the background sky. Hence, alternative techniques need to be considered for determining whether there exists a significant population of extragalactic objects with optically LSB. Searches for galaxies using the 21-cm line of atomic hydrogen provide one such alternative method. If LSB galaxies have a similar hydrogen content to galaxies of higher surface brightness, then we might expect that a 21-cm survey will not be biased against LSB galaxies.

However, the detection of a galaxy in a 21-cm survey is a function of both its H I column density and its H I mass. If a galaxy has a column density below the column density limit of the survey then it will never be detected whatever its total H I mass. Assuming LSB galaxies have similar H I content to brighter galaxies but that this is distributed over a larger surface area, then we would expect LSB objects to have lower H I column densities. Previous H I surveys have not generally had long enough integration times to search to...
sufficiently low column densities to draw definite conclusions concerning the cosmic prevalence of gas-rich LSB galaxies. HIDEEP with its 9000 s beam$^{-1}$ integration time is the first survey with sufficient column density sensitivity to be able to place interesting limits on the existence and size of a low column density/LSB population. Two major conclusions from HIDEEP have been presented here.

First, all of the sources found in HIDEEP appear to be associated with an optical counterpart on our deep UK Schmidt R-band data. In other words, we have not found an intergalactic HI cloud down to our observational column density limit of $N_{\text{HI}}/\Delta V = 2.1 \times 10^{16}$ cm$^{-2}$, which corresponds to an $N_{\text{HI}}$ of 4.2 $\times 10^{18}$ cm$^{-2}$ for a typical galaxy velocity distribution ($\Delta V = 200 \text{ km s}^{-1}$) and $3.2 \times 10^{17}$ cm$^{-2}$ for a typical QSOAL dispersion (15 km s$^{-1}$). Wherever neutral hydrogen is found it is accompanied by a visible population of stars above our surface-brightness limit of 26.5 $\text{ mag arcsec}^{-2}$ ($\sim$27.5 mag arcsec$^{-2}$ in $R$).

Secondly, if we infer the HI sizes of the HIDEEP detections from their optical sizes, then we can derive HI column densities for them. These derived column densities are all $\gg 10^{20}$ cm$^{-2}$, more than an order of magnitude above our observational limit. Assuming that our method of inferring HI size from optical size is robust, then this result implies that there is no significant population of galaxies with HI column densities $\lesssim 10^{20}$ cm$^{-2}$. We are currently undertaking a VLA and ATCA survey of all the HIDEEP sources in order to measure their column densities directly. This will enable us to test this result without having to infer HI size from optical size.

Possible physical explanations for this intriguing second result are discussed in detail elsewhere (Disney & Minchin 2003). Ionization is unlikely to be responsible since the intergalactic radiation field locally is at least an order to magnitude too small (Scott et al. 2002). Another possibility, raised in the early days of 21-cm astronomy, is ‘freezing out’, i.e. that the 21-cm spin temperature of low column density objects may fall to the cosmic background temperature, rendering such clouds invisible in emission.

The cosmic significance of gas-rich low-surface brightness galaxies will be the subject of a subsequent paper based on this same data (Minchin et al. 2003, in preparation). However, the fact that we have not found a single galaxy in HI that cannot be seen in our optical data suggests that there cannot be large numbers of gas-rich extremely LSB galaxies or intergalactic clouds.

If our second result is confirmed by the follow-up VLA and ATCA observations, then this will imply that HI surveys need not have column density limits much lower than $\sim 10^{20}$ cm$^{-2}$, since few galaxies would appear to have column densities lower than this. In particular, this would imply that previous large-area, shallow surveys, e.g. HIPASS and HIJASS, will have missed many low column-density objects. However, long integrations using telescopes with smaller beams would improve the statistics on the numbers of low-mass, low column-density sources.

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APPENDIX A: DERIVATION OF THE SURFACE BRIGHTNESS–COLUMN-DENSITY RELATION

For any given area the H\textsubscript{I} surface density and the optical surface brightness are related by

$$\Sigma_{\text{HI}} \left( \frac{M_{\text{HI}}}{L_B} \right) = \frac{1}{\Omega F} \times \frac{1}{\sqrt{\theta^2 / D^2}} \times \frac{1}{\mu_{\text{mean}}},$$  \hspace{1cm} (A1)

where $\Sigma_{\text{HI}}$ is the H\textsubscript{I} surface density and $\Sigma_B$ is the $B$-band optical surface brightness, averaged over the region, and $M_{\text{HI}}$ and $L_B$ are the H\textsubscript{I} mass and the $B$-band luminosity within the same region. As 1 $M_\odot$ pc\textsuperscript{-2} is approximately equal to an H\textsubscript{I} column density of $10^{20.1}$ cm\textsuperscript{-2} and 1 $L_\odot$ pc\textsuperscript{-2} is approximately equal to a surface brightness of 27.05 $B$ mag arcsec\textsuperscript{-2}, this gives the scaling relationship:

$$N_{\text{HI}} \simeq 10^{20.1} \left( \frac{M_{\text{HI}}}{L_B} \right) 10^{0.427 - \mu_{\text{mean}}},$$ \hspace{1cm} (A2)

where $N_{\text{HI}}$ is the H\textsubscript{I} column density in units of cm\textsuperscript{-2} and $\mu_{\text{mean}}$ is the average optical surface brightness in units of mag arcsec\textsuperscript{-2} taken over the same area as $N_{\text{HI}}$. This can be rewritten as

$$\mu_{\text{mean}} \simeq 2.5 \times 30.1 + \log \left( \frac{M_{\text{HI}}}{L_B} \right) - \log (N_{\text{HI}}).$$ \hspace{1cm} (A3)

This relation can be adapted to relate the central surface brightness of a galaxy to its average H\textsubscript{I} column density if certain assumptions are made concerning the size of the H\textsubscript{I} disc. Cayatte et al. (1994) found that $R_{\text{HI}} \simeq 1.7 R_{25}$. This scaling will obviously not hold for LSB galaxies, some of which may not even have a $\mu_{\text{sys}} = 25$ isophote, but for a Freeman law galaxy $R_{25} = 3.1$ scalelengths and it therefore seems reasonable to assume that $R_{\text{HI}} = 3.1 \times 1.7 = 5.25$ scalelengths. Assuming also that $M_{\text{HI}}/L_B = 0.3 M_\odot/L_\odot$ (average value from Roberts & Haynes 1994), we obtain $\mu_0 \simeq 2.5 \times 28.95 - \log (N_{\text{HI}})$, \hspace{1cm} (A4)

which can be used to work out an approximate equivalent central surface-brightness limit for H\textsubscript{I} surveys.

APPENDIX B: COLUMN-DENSITY SENSITIVITY

The signal entering the receiver is measured in terms of the antenna temperature $T_A$, where

$$k T_A = S_c D^2.$$ \hspace{1cm} (B1)

$S_c$ is the strength of the source in flux units and $D$ is the dish diameter. For a significant detection $T_A$ should exceed the uncertainty in the system power by some signal-to-noise ratio $\sigma$, i.e.

$$T_A \geq \sigma \frac{T_{\text{sys}}}{\sqrt{\ln \Delta V}}.$$ \hspace{1cm} (B2)

which is the usual ‘antenna equation’ derived from the bandwidth theorem.

In the Rayleigh–Jeans regime, surface brightness is conventionally expressed in terms of the brightness temperature

$$T_B = \frac{\lambda^2}{2k} \frac{S_c}{\Delta \Omega},$$ \hspace{1cm} (B3)

where $\Delta \Omega$ is the solid angle of the source. For H\textsubscript{I} galaxies quantum mechanics yields

$$\frac{N_{\text{HI}}}{\Delta V} = 1.8 \times 10^{18} T_B,$$ \hspace{1cm} (B4)

where $N_{\text{HI}}$ is the column density in cm\textsuperscript{-2} and $\Delta V$ is the velocity width of the line.

The antenna equation (B2) can now be rewritten as

$$\frac{N_{\text{HI}}}{\Delta V} \geq 1.8 \times 10^{18} \frac{\lambda^2}{2D^2 \Delta \Omega} \frac{\sigma T_{\text{sys}}}{\sqrt{\ln \Delta V \Delta V_{\text{ch}}}}.$$ \hspace{1cm} (B5)

where we have replaced $\Delta V$ with $\Delta V_{\text{ch}}$ because here we are interested in a peak-flux-limited survey.

If we now substitute in the beam size, $\Omega_b = 1.13(\lambda/D)^2$, and the channel velocity width $\Delta V_{\text{ch}} = (c/\nu_{\text{ch}}) \times \Delta \nu_{\text{ch}}$, we obtain

$$\frac{N_{\text{HI}}}{\Delta V} \geq 5.5 \times 10^{16} \frac{\Omega_b}{\Delta \Omega} \frac{\sigma T_{\text{sys}}}{\sqrt{\nu_{\text{ch}} \Delta V_{\text{ch}}}}.$$ \hspace{1cm} (B6)

So, if the source fills the beam, i.e. $\Omega_b/\Delta \Omega = 1$

$$\frac{N_{\text{HI}}}{\Delta V} \geq 5.5 \times 10^{16} \frac{\sigma T_{\text{sys}}}{\sqrt{\nu_{\text{ch}} \Delta V_{\text{ch}}}}.$$ \hspace{1cm} (B7)

which agrees with equation (8), and is indeed independent of the telescope diameter. For HIDEEP, $T_{\text{sys}} = 26 K$, $t_{\text{ch}} = 9000 s$, $\Delta V_{\text{ch}} = 13.2$ km s\textsuperscript{-1} and if $\sigma = 5$

$$\frac{N_{\text{HI}}}{\Delta V} \geq 2.1 \times 10^{16} \text{ cm}^{-2} \text{ (km s}^{-1})^{-1}.$$ \hspace{1cm} (B8)

For an optimally smoothed survey limited only by the signal-to-noise ratio of the total flux of the galaxy rather than the flux in a single channel, one would replace $\Delta V_{\text{ch}}$ by $(\Delta V/\nu_{\text{ch}})$ in equation (B7) and reach (Disney & Banks 1997)

$$\left( \frac{N_{\text{HI}}}{\Delta V} \right) > 1.8 \times 10^{18} \sigma T_{\text{sys}} \sqrt{\frac{1}{\Delta V t_{\text{ch}}}}.$$ \hspace{1cm} (B9)

APPENDIX C: CALCULATING MINIMUM COLUMN-DENSITY SENSITIVITY FROM THE LOWEST FLUX SOURCES ACTUALLY DETECTED

At any distance a source that is just detectable because of its H\textsubscript{I} mass, and which just fills the beam, will have the minimum column density the survey is capable of detecting

$$N_{\text{HI}} = 5 \times 10^{20} \frac{M_{\text{HI}}}{\sigma \theta^2 d_{\text{pc}}^2}.$$ \hspace{1cm} (C1)

where $\theta$ is the angular diameter of the source in radians, and $d_{\text{pc}}$ is its distance in parsecs. By a well-known relation $M_{\text{HI}}$ is related to the flux $F_{\text{HI}}$ by

$$M_{\text{HI}} = 2.356 \times 10^5 \frac{F_{\text{HI}} d_{\text{pc}}^2}{\sigma \theta^2},$$ \hspace{1cm} (C2)

and therefore we can substitute this into the equation above to give

$$N_{\text{HI}} = \frac{2.356 \times 10^5 F_{\text{HI}} d_{\text{pc}}^2}{\sigma \theta^2},$$ \hspace{1cm} (C3)

therefore

$$N_{\text{HI}}^{\min} = 4.5 \times 10^{20} \frac{F_{\text{HI}}^{\min}}{\sigma \theta^2},$$ \hspace{1cm} (C4)

where $\theta'$ is the source diameter in arcmin. Putting $\theta'$ equal to the beam diameter, and $F_{\text{HI}}$ to the lowest flux measured in the survey will yield the column-density limit of the survey at the velocity width of that source. Of more interest is putting in the lowest value of $F_{\text{HI}}/\Delta V$, which allows the column-density limit to be found at all velocity widths:

$$\left( \frac{N_{\text{HI}}}{\Delta V} \right)^{\min} = 4.5 \times 10^{20} \left( \frac{F_{\text{HI}}}{\Delta V} \right)^{\min} \frac{1}{\theta^2},$$ \hspace{1cm} (C5)

which is equation (12) in the text.

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