An H I survey for protogalaxies in the Centaurus and Fornax galaxy clusters

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Accepted 1997 January 13. Received 1996 December 11; in original form 1996 August 19

ABSTRACT

The results of 21-cm neutral hydrogen survey observations, made using the 64-m Parkes telescope, are presented for two 8° by 8° fields, centred on the Centaurus and Fornax galaxy clusters, and a smaller 1.5° field in Eridanus. The purpose of the observations was to search for extended H I clouds with no clear optical counterparts. 31 previously catalogued galaxies were detected, with H I parameters for 16 being listed for the first time. One previously uncatalogued dwarf galaxy ('Wombat 1', J0341–3851) was found near the Fornax cluster. Australia Telescope Compact Array observations give an H I mass of \(8 \times 10^7 \, M_\odot\) and a diameter of 4 kpc for this object, which is also visible on UKST survey plates. However, no clouds with optically invisible counterparts were detected. We deduce a 99 per cent confidence limit on the total H I density of such objects in the cluster and near-cluster environment of \(\Omega_{\text{HI}} < 10^{-2} h^{-1} (\delta v/100 \, \text{km s}^{-1})\).

Key words: surveys – galaxies: clusters: individual: Centaurus – galaxies: clusters: individual: Eridanus – galaxies: clusters: individual: Fornax – radio lines: galaxies.

1 INTRODUCTION

Most normal galaxies are believed to form during the non-linear gravitational collapse of primordial gas clouds. The collapse is initiated by perturbations of the gas density which grow with time. Massive galaxies will form rapidly from larger amplitude perturbations, whilst less massive galaxies are expected to form more gradually from smaller amplitude perturbations. It is possible that gas clouds which reside within amplitude perturbations smaller than some limit may still be in a state of collapse at the present epoch, not having reached the threshold density for forming stars (Toomre 1964; Kennicutt 1989). The number of such protogalaxies appears to be strongly dependent on total mass, and the UV photoionizing background (Chiba & Nath 1994; Quinn, Katz & Efstathiou 1996). Once star formation has begun, the continued existence of such galaxies is dependent on the ratio of kinetic energy imparted by stellar and supernova-driven winds to the gravitational binding energy of the interstellar medium (de Young & Heckman 1994). The goal in the present paper is to search for protogalaxies in the nearby Universe using the 21-cm line of neutral hydrogen. Such a survey is also sensitive to optically faint, but gas-rich, galaxies and to tidal debris such as the Leo ring (Schneider 1989).

Searches for nearby galaxies in the 21-cm line of H I had by 1990 covered a bandwidth-pointing product (i.e. \(\Sigma N_i B_i\), where survey \(i\) consists of \(N_i\) discrete pointings at bandwidth \(B_i\)) of only \(\sim 350\,\text{GHz}\) (Briggs 1990), corresponding to \(\sim 2\) per cent of the sky to a redshift depth of \(z = 0.01\). Krumm & Brosch (1984) searched unsuccessfully for H I clouds in cosmic voids, and concluded that clouds of mass \(10^{10} - 10^{11} \, h^{-1} \, M_\odot\) contribute no more than \(4 \times 10^{-4} h^{-1}\) to \(\Omega_0\) in the Perseus–Pisces void and no more than \(2 \times 10^{-3} h^{-1}\) to \(\Omega_0\) in the Hercules void. In a survey of 153 square degrees, Fisher & Tully (1981) failed to detect any H I clouds that were not associated with an optically visible counterpart, and thus determined that the mass in intergalactic H I clouds of mass \(10^{7} - 10^{10} \, h^{-1} \, M_\odot\) contributes less than \(5 \times 10^{-4} h^{-1}\) to \(\Omega_0\). However, Briggs (1990) points out that the short integration times of these and previous searches mean that they were completely insensitive to column densities much less than \(10^{20}\,\text{cm}^{-2}\). As a result, the number density of large-diameter, low H I surface brightness objects with \(N(HI) < 5 \times 10^{-9}\,\text{cm}^{-2}\) is virtually unconstrained in such observations.

Hoffman, Lu & Salpeter (1992) report on an H I survey aimed at detecting low-mass gas clouds and gas-rich dwarf galaxies. Their survey at Arecibo was directed towards the void nearest to the Local Supercluster, and failed to detect any new objects within the void, excepting two new members of a previously known group. Consequently Hoffman et al. (1992) constrain the \(\Omega_0\) contribution of void-filling gas clouds with \(M_{H I} > 5 \times 10^6 \, M_\odot\) to be less than 5 per cent of closure density.

Despite these null detection surveys, a number of very interesting, low surface brightness galaxies have been discovered in H I observations. One such object is H I 1225+01 which was reported as a serendipitous discovery by Giovanelli & Haynes (1989) during routine 21-cm observations with the Arecibo telescope. This object lies south of the Virgo cluster at a velocity of \(1275\,\text{km s}^{-1}\). The H I
mass of the object was determined to be greater than $4 \times 10^9 M_\odot$, and the total mass to be in excess of $2 \times 10^{10} M_\odot$. At the time, there was no evidence for an associated stellar population. However, Impey et al. (1990) and Djorgovski (1990) reported the detection of a faint optical counterpart associated with the north-eastern end of the cloud, implying the presence of star formation in one part of the object. Salzer et al. (1991) showed the colours and metallicity of this object to be similar to those of other dwarf irregular galaxies.

The cloud, implying the presence of star formation in one part of the object. Salzer et al. (1991) showed the colours and metallicity of this object to be similar to those of other dwarf irregular galaxies. No optical emission associated with the south-western clump has been seen. High-resolution VLA observations by Chengalur, Giovanelli & Haynes (1995) appear to show that the two clumps are independently rotating systems, now undergoing a prograde encounter and forming a tidal bridge between the two systems. The lack of optical emission from the south-western clump is explained by the H$\alpha$ surface density being less than Toomre's (1964) gravitational instability threshold, and therefore it is a candidate for a protogalaxy in the sense defined above.

More sensitive, pencil-beam surveys for H I galaxies have been conducted using the VLA by Weinberg et al. (1991) and Szomoru et al. (1994). These surveys produced the first H I-discovered galaxy in the Boötes void (Szomoru et al. 1993), and have also produced a small sample of H I-selected objects, adding to the H I-selected sample produced by blind searches with the former Green Bank telescope (Henning 1995). Although such samples are dominated by optically faint objects, these objects appear not to dominate the H I density of the local Universe.

In this paper, we present results from a series of 21-cm observations of the Centaurus and Fornax southern galaxy clusters, and the Eridanus group, made with the Parkes telescope. These observations are part of our continuing programme of blind searches for extremely low surface brightness galaxies with H I masses in the range $10^9 - 10^{12} M_\odot$. In this programme, the Australia Telescope Compact Array (ATCA) is being used to image selected 'blank' fields and probe the H I mass range $10^8 - 10^9 M_\odot$, whilst the Parkes telescope was used to search the H I mass range $10^9 - 10^{12} M_\odot$.

2 OBSERVATIONS

2.1 The fields

The Centaurus cluster has been studied extensively at optical wavelengths (Dickens, Currie & Lucey 1986; Lucey, Currie & Dickens 1986a,b) and in the X-ray band (Matilsky, Jones & Forman 1985; Mohr, Fabricant & Geller 1993). Lucey et al. (1986a) found a bimodal velocity distribution for the Centaurus cluster. The lower velocity component has a mean velocity of 3041 km s$^{-1}$ and a velocity dispersion of 586 km s$^{-1}$, and is centred on the large elliptical galaxy NGC 4696. Matilsky et al. (1985) found that at a gas temperature of 2.1 keV the X-ray luminosity of NGC 4696 is $7 \times 10^{42}$ erg s$^{-1}$. The higher velocity component has a mean velocity of 4570 km s$^{-1}$ and a velocity dispersion of 280 km s$^{-1}$, and is centred on the large elliptical galaxy NGC 4709. Because of the smaller velocity dispersion of this component, the X-ray luminosity is expected to be lower by a factor of $\sim 1/25$ than that of the dynamical centre of the lower velocity component (Matilsky et al. 1985).

The Fornax cluster is a small, dense concentration of early-type galaxies and has been the subject of several investigations of galaxy populations (e.g. Ferguson 1989). The cluster lies in the velocity range 700–2200 km s$^{-1}$, and is centred on the luminous elliptical NGC 1399. X-ray observations of NGC 1399 have detected emission corresponding to a gas temperature of 1.4 keV, extending beyond a 360-kpc radius (Ikebe et al. 1992). Bland-Hawthorn et al. (1995) reported the discovery of an ionized hydrogen cloud near Fornax A. The most recent H I observations of optical galaxies in Fornax have been completed by Schröder (1995) and Bureau, Mould & Staveley-Smith (1996).

To enhance our detection prospects, we chose the Centaurus and Fornax regions as representing regions of above-average galaxy density. The surveyed fields extend well beyond the actual clusters, allowing us to search a continuous range of galaxy environments. The bias factor (Kaiser 1984) for low-mass galaxies may be lower than for high-mass galaxies, although the existence of the Virgo protogalaxy demonstrates that the near-cluster environment does not exclude such objects.

The Eridanus group is a prominent system in a filamentary structure observed in maps of the Southern Sky Redshift Survey (da Costa et al. 1988). Eridanus has been studied in considerable detail at optical wavelengths by Ferguson & Sandage (1990, 1991), and has been the subject of a dynamical study by Willmer et al. (1989). Of particular interest in Eridanus is the group of galaxies around NGC 1407. The peculiar velocity of NGC 1400 (1100 km s$^{-1}$ with respect to the group) implies a high mass-to-light ratio independently of whether or not it belongs to the group (Quintana, Fouque & Way 1994), and hence offers an interesting target for neutral hydrogen observations.

2.2 Observations and reduction

We have selected two $8^\circ \times 8^\circ$ fields, one centred on the Fornax cluster and one on the Centaurus cluster, and one $1^\circ 75 \times 1^\circ 75$ field centred on NGC 1407 in Eridanus, for 21-cm spectral line observations. The survey observations were made on 1991 March 19–21, 1991 August 13, 1993 June 16–21 and 1994 September 15–19, with follow-up observations on 1995 September 8–10, with the Parkes 64-m radio telescope in New South Wales, Australia. The distribution of galaxies from the ESO/Uppsala Survey of the ESO(B) Atlas (Lamberts 1982) over the three fields is shown in Figs 1, 2 and 3. These figures depict graphically the large range of galaxy environments probed by our surveys. For the Centaurus and Fornax fields, our surveys extend well beyond the dense cluster centres, whilst for the smaller Eridanus field, we search only in the dense group centre.

For the 1991 March observations, the old Parkes telescope correlator (Ables et al. 1975) was used. The total spectral bandwidth of 10 MHz over 256 channels was increased to 17.5 MHz by splitting the desired velocity range into two slightly overlapping frequency bands and observing each band independently. For the remainder of the observations, the new Australia Telescope correlator (Wilson et al. 1992) was used with a spectral bandwidth of 32 MHz over 1024 channels. For the 1991 observations, the system noise temperature was $\sim 40$ K, whilst for the 1993–95 observations new receivers provided lower system temperatures of $\sim 25$ K. The system response was calibrated daily against the radio source Hydra A. The beamwidth at half-maximum power for 21-cm observations with the Parkes telescope is 15 arcmin.

Observations were made by pointing the telescope at pre-determined grid positions for 180 s for the Centaurus and Fornax fields, and 2100 s (10 frames of 210 s) for the Eridanus field. The grids for the Centaurus and Fornax fields were composed of two overlaid sub-grids, each consisting of 16 x 16 pointings spaced by 30 arcmin in RA and 30 arcmin in Dec. The two sub-grids were offset from one another by 15 arcmin in each direction, as shown in Figs 1 and 2. For the Eridanus field, the grid was simply a square lattice of $7 \times 7$.
pointings spaced by 15 arcmin (i.e. the beamwidth), as shown in Fig. 3. All fields were observed row by row, in order of increasing RA within a row. The observing parameters are given in Table 1. All velocities determined in this paper are given as optical velocities.

The spectral analysis was performed in SLAP (Spectral Line Analysis Package). To remove the bandpass, each 'on' spectrum was normalized with an 'off' spectrum, which was formed from the weighted average of two spectra on either side of the 'on' spectrum. This technique yielded flat baselines for ~80 per cent of the data. The two polarizations were added, and the spectra were Hanning-smoothed in the velocity domain, resulting in a velocity resolution of twice the channel width. The typical rms spectral noise is given in Table 1 for each survey observing session. The value given is the median of the noise measurements from all spectra taken during an observing session. The minimum detectable neutral hydrogen column density for our surveys was \(10^{19}\) atom cm\(^{-2}\).

Follow-up observations in 1995 September were used to re-observe \(\text{H}\,\text{i}\) cloud candidates that were identified in the survey, but not with high enough confidence to be matched to previously catalogued galaxies. For these observations, the 3-min integration was retained, but typically repeated eight times, resulting in higher sensitivity. Reference ('off') positions containing no known galaxies nearer than 15 arcmin were chosen individually for each candidate, and were offset from the candidate by 4–10 min in RA to minimize change in ground spillover when switching between the source and reference positions. For those candidates that reappeared during follow-up observations but still with no catalogued galaxy within 10 arcmin, further spectra were observed at ±7.5–arcmin offsets in RA and Dec. to obtain better positions for optical identification.

### 3 RESULTS

After follow-up observations, 23 detections in the Centaurus field were confirmed and identified with optically catalogued galaxies. These are listed in Table 2, and the 21-cm profiles are shown in Fig. 4. In the Fornax field, nine detections were confirmed (Table 3 and Fig. 5), and eight of these were identified with optically catalogued galaxies. Only one survey position showed detectable 21-cm emission, yet had no obvious association with any nearby catalogued
Table 1. Velocity coverage and observational parameters.

<table>
<thead>
<tr>
<th>Date</th>
<th>Field</th>
<th>Pointings</th>
<th>Velocity (km s⁻¹)</th>
<th>Channel width (km s⁻¹)</th>
<th>Median noise (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 1991</td>
<td>Cen</td>
<td>112</td>
<td>1811-4980</td>
<td>8.2</td>
<td>17.1</td>
</tr>
<tr>
<td>Jun 1993</td>
<td>Cen</td>
<td>400</td>
<td>501-4877</td>
<td>6.6</td>
<td>10.8</td>
</tr>
<tr>
<td>Mar 1991</td>
<td>For</td>
<td>128</td>
<td>100-3336</td>
<td>8.2</td>
<td>30.6</td>
</tr>
<tr>
<td>Aug 1991</td>
<td>For</td>
<td>32</td>
<td>501-4877</td>
<td>6.6</td>
<td>18.9</td>
</tr>
<tr>
<td>Jun 1993</td>
<td>For</td>
<td>160</td>
<td>501-4877</td>
<td>6.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Sep 1995</td>
<td>For</td>
<td>192</td>
<td>501-4877</td>
<td>6.6</td>
<td>11.9</td>
</tr>
<tr>
<td>Sep 1994</td>
<td>Eri</td>
<td>49</td>
<td>349-4530</td>
<td>6.6</td>
<td>5.0</td>
</tr>
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Table 2. H I detections – the Centaurus cluster.

<table>
<thead>
<tr>
<th>Survey pointing centre (B1950.0)</th>
<th>Central velocity (km s⁻¹)</th>
<th>H I profile offset from pointing centre (arcmin)</th>
<th>85</th>
<th>13.6</th>
<th>322-G007</th>
<th>3179 (5)</th>
<th>3.6</th>
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<td>122306 - 4030</td>
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<td>75</td>
<td>85</td>
<td>13.6</td>
<td>322-G007</td>
<td>3179 (5)</td>
<td>3.6</td>
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<td>122425 - 3615</td>
<td>4095</td>
<td>50</td>
<td>40</td>
<td>12.2</td>
<td>380-G029</td>
<td>4063 ± 10 (8)</td>
<td>6.4</td>
</tr>
<tr>
<td>122543 - 3700</td>
<td>3053</td>
<td>115</td>
<td>78</td>
<td>10.2</td>
<td>380-G034</td>
<td>3041 (10)</td>
<td>5.4</td>
</tr>
<tr>
<td>122543 - 3730</td>
<td>3355</td>
<td>148</td>
<td>29</td>
<td>10.8</td>
<td>322-G016</td>
<td>3342 (5)</td>
<td>3.6</td>
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<tr>
<td>122543 - 3800</td>
<td>3324</td>
<td>134</td>
<td>44</td>
<td>11.4</td>
<td>322-G018</td>
<td>3322 (5)</td>
<td>2.4</td>
</tr>
<tr>
<td>122543 - 4300</td>
<td>2916</td>
<td>173</td>
<td>167</td>
<td>22.5</td>
<td>268-G010</td>
<td>2915 ± 8 (7)</td>
<td>2.4</td>
</tr>
<tr>
<td>122938 - 4015</td>
<td>2696</td>
<td>239</td>
<td>42</td>
<td>9.9</td>
<td>322-G025</td>
<td>2914 ± 42 (9)</td>
<td>6.5</td>
</tr>
<tr>
<td>123215 - 3645</td>
<td>4247</td>
<td>23</td>
<td>32</td>
<td>9.7</td>
<td>380-G046</td>
<td>4407 (5)</td>
<td>9.5</td>
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<td>123215 - 3945</td>
<td>3574</td>
<td>66</td>
<td>50</td>
<td>8.3</td>
<td>322-G029</td>
<td>3538 ± 9 (2)</td>
<td>10.4</td>
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<td>123452 - 4021</td>
<td>2978</td>
<td>265</td>
<td>63</td>
<td>11.0</td>
<td>322-G036</td>
<td>3022 ± 15 (3)</td>
<td>3.3</td>
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<td>123610 - 4030</td>
<td>3715</td>
<td>290</td>
<td>40</td>
<td>10.4</td>
<td>322-G044</td>
<td>3775 ± 20 (1)</td>
<td>8.6</td>
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<td>123728 - 4015</td>
<td>3270</td>
<td>109</td>
<td>53</td>
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<td>322-G046</td>
<td>3149 ± 8 (7)</td>
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<td>123728 - 4045</td>
<td>2592</td>
<td>363</td>
<td>51</td>
<td>10</td>
<td>322-G052</td>
<td>2562 ± 8 (7)</td>
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<tr>
<td>123847 - 4021</td>
<td>3269</td>
<td>172</td>
<td>102</td>
<td>12.9</td>
<td>381-G008</td>
<td>3285 ± 7 (3)</td>
<td>7.4</td>
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<tr>
<td>124123 - 4000</td>
<td>1140</td>
<td>92</td>
<td>29</td>
<td>8.4</td>
<td>322-G068</td>
<td>2953 ± 37 (9)</td>
<td>3.5</td>
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<tr>
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<td>2910</td>
<td>220</td>
<td>77</td>
<td>7.5</td>
<td>322-G067</td>
<td>2953 ± 37 (9)</td>
<td>3.5</td>
</tr>
<tr>
<td>124242 - 4345</td>
<td>4883</td>
<td>253</td>
<td>68</td>
<td>14.0</td>
<td>268-G037</td>
<td>4947 ± 17 (7)</td>
<td>4.3</td>
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<tr>
<td>124755 - 4215</td>
<td>3153</td>
<td>100</td>
<td>37</td>
<td>9.2</td>
<td>323-G014</td>
<td>3125 ± 39 (5)</td>
<td>11.9</td>
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<tr>
<td>125032 - 3845</td>
<td>4307</td>
<td>412</td>
<td>65</td>
<td>10.8</td>
<td>323-G025</td>
<td>4229 ± 6 (4)</td>
<td>7.6</td>
</tr>
<tr>
<td>125427 - 3930</td>
<td>2910</td>
<td>196</td>
<td>37</td>
<td>8.9</td>
<td>323-G049</td>
<td>3914 ± 59 (9)</td>
<td>1.9</td>
</tr>
<tr>
<td>125704 - 4300</td>
<td>3255</td>
<td>196</td>
<td>36</td>
<td>12.2</td>
<td>269-G028</td>
<td>3170 ± 59 (9)</td>
<td>2.3</td>
</tr>
<tr>
<td>130059 - 4115</td>
<td>2592</td>
<td>255</td>
<td>207</td>
<td>13.0</td>
<td>323-G074</td>
<td>2587 ± 5 (7)</td>
<td>7.1</td>
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<tr>
<td>130336 - 4115</td>
<td>3116</td>
<td>187</td>
<td>28</td>
<td>10.3</td>
<td>323-G082</td>
<td>3098 (5)</td>
<td>9.7</td>
</tr>
</tbody>
</table>

1 Aaronson et al. (1989).
3 Aguero et al. (1994).
6 Lauberts (1982).
10 NASA/IPAC Extragalactic Database.

galaxy (B1950 survey pointing 033827 - 3900, Fornax). The detection in Table 2 that has been identified with a catalogued galaxy and has no known redshift (B1950 pointing 124123-4000) is believed to be associated with the galaxy because of its proximity to the centre of the beam, and its visual appearance. The detections at 033107 - 3630 (B1950) and 033220 - 3615 (B1950) in Fornax are of the same galaxy (ESO 358-G 017 or NGC 1365), which is a large and bright barred spiral. The H I velocities differ because the pointings are directed at different parts of the galaxy. We remind the reader that the 21-cm profiles shown in this paper were obtained with the telescope offset from the sources by typically 2-8 arcmin, and, accordingly, the profile fluxes are diminished, and some profiles will be distorted.

As well as the previously uncatalogued object, one of the Fornax
Figure 4. Centaurus H I profiles. All velocity axes span 1400 km s⁻¹; refer to Table 2 for signal and noise levels.
Figure 4 – continued
An $H_{\text{i}}$ survey for protogalaxies

Figure 4 – continued
1997MNRAS.288..307B

With no clear optical counterpart visible on the Digitized Sky Survey before (Huchtmeier & Richter 1989), 3.1 ATCA observations of PKS HI J0341-3851: Wombat I.

322-G 007, 380-G 029, 380-G 016, 322-G 018, 322-G 025, 380-G 046, 380-G 034, 380-G 008, 322-G 068, 322-G 067, 323-G 014, 323-G 049 and 323-G 082) have not been detected in HI. The 21-cm spectrum for this offset is shown in Fig. 6. This galaxy, which we name Wombat I, is located at right ascension 03 $h$ 39 $m$ 09 $s$ and has a velocity width of 62 km s$^{-1}$ is overlaid on the DSS image in Fig. 7. The peak of the 21-cm emission is located at right ascension 03 $h$ 39 $m$ 09 $s$ 11' and has a velocity width of 62 km s$^{-1}$. The total HI mass of the galaxy is $8 \times 10^{44}$ $M_\odot$, and at a distance of 8.6 $h^{-1}$ Mpc half of the HI gas is contained within 4 kpc. Whilst these parameters suggest that Wombat I is a particularly unremarkable galaxy, its velocity places it at the near edge of the Fornax cluster, and raises the possibility that the cluster extends further south than previously thought.

Interestingly, Wombat I is similar to Malin I (Bothun et al. 1987) in visual appearance, and the lowest contour in Fig. 7 suggests that the HI may extend asymmetrically towards the south-west. Further 21-cm mapping of Wombat I would be worthwhile to establish whether this is the case. If the HI in Wombat I is elongated with respect to the optical galaxy, as seen in Malin I, there may be interesting comparisons which can be made between these two systems.

### 4 ANALYSIS

Overall, no HI gas clouds were detected in the three surveys described. This makes it possible to place limits on the contribution of such clouds to the total mass density in each field, and hence assess the cosmological significance of HI clouds at the present epoch. We first construct a function which reflects the volume covered by such clouds to the total mass density in each field, and hence yield the total mass density residing in HI clouds in the survey fields.

#### 4.1 Volume coverage

The total HI mass of a cloud ($M_{HI}$) that is unresolved by the telescope beam, and whose HI is optically thin, is given by the standard formula

$$M_{HI} = 2.356 \times 10^{2} \int S(v) dv M_\odot,$$

where $d$ is the distance in Mpc to the galaxy, $S(v)$ is the flux density

1. The velocity resolution for this correlator configuration is equal to 1.21 times the channel spacing.

2. In this paper, $h$ is Hubble's constant expressed in units of 100 km s$^{-1}$ Mpc$^{-1}$.

### Table 3. HI detections – the Fornax cluster.

<table>
<thead>
<tr>
<th>Survey pointing centre (B1950.0)</th>
<th>Central velocity ($\Delta \nu$) (km s$^{-1}$)</th>
<th>Peak flux (mJy)</th>
<th>rms noise (mJy)</th>
<th>Catalogue data</th>
</tr>
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<tbody>
<tr>
<td>032007 – 3745</td>
<td>1624</td>
<td>47</td>
<td>96</td>
<td>SGC 0320.1-3747</td>
</tr>
<tr>
<td>032234 – 3645</td>
<td>1355</td>
<td>239</td>
<td>100</td>
<td>357-G 026</td>
</tr>
<tr>
<td>032347 – 3630</td>
<td>997</td>
<td>161</td>
<td>306</td>
<td>357-G 029</td>
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<tr>
<td>033107 – 3630</td>
<td>1826</td>
<td>68</td>
<td>247</td>
<td>357-G 0028</td>
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<td>033827 – 3900</td>
<td>824</td>
<td>63</td>
<td>29</td>
<td>358-G 017</td>
</tr>
<tr>
<td>034432 – 3515</td>
<td>1946</td>
<td>246</td>
<td>65</td>
<td>358-G 017</td>
</tr>
<tr>
<td>034925 – 3845</td>
<td>860</td>
<td>98</td>
<td>45</td>
<td>302-G 014</td>
</tr>
</tbody>
</table>

1. No ESO identification available, SGC identification from Corwin, de Vaucouleurs & de Vaucouleurs (1985).

### References

- Barnes et al. (1996)
- Fouqué et al. (1990).
- Lauberts (1982).
Figure 5. Fornax H I profiles. All velocity axes span 1400 km s$^{-1}$; refer to Table 3 for signal and noise levels.
expressed in mJy and $v$ is the velocity in km s$^{-1}$. The integral can be simplified by assuming that an $H_1$ cloud produces a rectangular line profile of amplitude $S$ mJy and width $\delta V$ km s$^{-1}$, i.e.,

$$\int S(v)dv = SS\delta V,$$

and thus

$$M_{H_1} = 2.356 \times 10^3 s^2 \delta V M_\odot.$$

To detect an $H_1$ cloud, it is necessary that the line profile amplitude be greater than the rms noise fluctuations in the underlying spectrum. We assume that the human visual system can reliably recognize features with signal-to-noise ratios of 3 or greater. Since all the spectra for the described surveys were visually inspected, we assume that all line profiles with $S > 3\sigma$ were detected, where $\sigma$ is the rms noise in an individual spectrum. For this paper, the telescope beam shape is taken as a Gaussian function,

$$B(r) = \exp(-a r^2),$$

with $a = 44.36$ deg$^{-2}$, and $M_0$ is the minimum mass that can be detected at the centre of the beam at redshift $V$:

$$M_0 = 7.07 V^2 \sigma (\delta V/100)^2 M_\odot.$$

Equation (4) gives the maximum distance away from the beam centre ($r_{\max}$) at which an $H_1$ cloud of mass $M_{H_1} \geq M_0$ can be detected, which is

$$r_{\max}^2 = \frac{1}{a} \ln (M_{H_1}/M_0),$$

and consequently the area searched for such clouds by a single beam pointing is given by $\pi r_{\max}^2$. The area searched for such clouds in the entire field ($A_e$), consisting of $N_p$ pointings, is thus

$$A_e(M_{H_1}, V) = \sum_{j=1}^{N_p} \frac{\pi}{a} \ln \left( \frac{M_{H_1}}{7.07 V^2 \sigma_j} \right),$$

with $M_{H_1}$ expressed in the units $(\delta V/100)^2 h^{-2} M_\odot$. Finally, the total volume probed for clouds of mass $M_{H_1}$ is given by

$$V(M_{H_1}) = \int A_e(M_{H_1}, V) \left( \frac{V}{100} \right)^2 \frac{dV}{100} h^{-2} \text{Mpc}^3,$$

where the integration extends over the velocity range of the cluster. We adopt the following cluster velocities: Centaurus 2400–4900 km s$^{-1}$, Fornax 700–2200 km s$^{-1}$ and Eridanus 600–2100 km s$^{-1}$.

### 4.2 Limits on the $H_1$ mass function

Following Shostak (1977), the $H_1$ mass function $[\phi(M_{H_1})]$ is defined such that the probability $p$ of detecting no $H_1$ clouds within a given mass decade is given by

$$p(M_{H_1}) = \exp[-\phi(M_{H_1}) \times \zeta(M_{H_1})].$$

Figure 6. The Parkes 21-cm spectrum leading to the discovery of Wombat I.

Figure 7. The $H_1$ distribution (contours) of Wombat I overlaid on to the optical emission (grey-scale) from the Digitized Sky Survey. The contours are at levels of 3.5, 7.0, 10.5, 14.0 and 17.5 mJy beam$^{-1}$. The beam is shown in the lower left corner.

Figure 8. Limits on the $H_1$ mass function for the three fields. $H_1$ mass is in units of $(\delta V/100)^2 h^{-2} M_\odot$. with a full width at half-maximum of 15 arcmin. So to detect a cloud at redshift $V$ km s$^{-1}$ and distance $r$ from the centre of the telescope beam, we require

$$M_{H_1} > \frac{M_0 B(0)}{B(r)},$$

where $B(r)$ is the beam profile:

$$B(r) = \exp(-a r^2),$$

with $a = 44.36$ deg$^{-2}$, and $M_0$ is the minimum mass that can be detected at the centre of the beam at redshift $V$:

$$M_0 = 7.07 V^2 \sigma (\delta V/100)^2 M_\odot.$$
Table 4. Limits on Ω_HI for the three survey fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Mass range (6V/100h⁻² M☉)</th>
<th>Ω_HI (upperlimit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centaurus</td>
<td>3.5 x 10⁶ - 3.5 x 10¹¹</td>
<td>9.3</td>
</tr>
<tr>
<td>Fornax</td>
<td>10⁶ - 10¹¹</td>
<td>8.9</td>
</tr>
<tr>
<td>Eridanus</td>
<td>10⁶ - 10¹¹</td>
<td>250.0</td>
</tr>
</tbody>
</table>

with ϕ(M_HI) defined as above. We require the combined probability of no detections in all decades to be 1 per cent, and so over three decades (see Shostak 1977 for further details)

ϕ(M_HI) = \frac{1.54}{\delta(M_HI)}.

(11)

Plots of ϕ(M_HI) versus H_I mass for the three surveys are given in Fig. 8.

Integration of the mass function derived above, over the three decades of H_I mass to which each survey was sensitive, yields a 99 per cent confidence limit to the total neutral hydrogen mass density residing in H_I clouds in the survey areas. Then, using the standard formula

Ω_H_I = \frac{8\pi G ρ_{HI}}{3H₀²}.

(12)

the contribution to the cosmological density parameter of H_I clouds (Ω_H_I) can be determined. The results are shown in Table 4 for the three survey areas.

5 DISCUSSION

5.1 The H_I mass function

The limiting H_I mass functions in Fig. 8 are typical of such functions determined with blind 21-cm surveys. Working from large H_I masses towards smaller H_I masses, the limiting density function remains constant while the survey volume is fully sampled (and limited by receiver bandwidth), then begins to rise as the survey becomes less sensitive to smaller H_I clouds. Eventually an H_I mass is reached beyond which the survey is unable to detect objects even at the beam centre. For the most distant field, Centaurus, this limiting H_I mass is ~3.5 x 10⁶ M☉, whilst for the closer fields it is below 10⁶ M☉.

Typical diameters for H_I-rich galaxies are 5–50 kpc, and in our calculations we have assumed that H_I clouds will subtend solid angles less than that of the telescope beam. For the Centaurus cluster, this approximation is valid, since the beamwidth ranges from 100 h⁻¹ kpc at the near side of the cluster to 210 h⁻¹ kpc at the far side. However, for the Fornax and Eridanus clusters, the beamwidth ranges from 30 to 92 h⁻¹ kpc, and large H_I-rich galaxies or clouds will often lie partly outside the beam. This does not necessarily decrease the chances of detecting large-scale H_I discs in these two clusters, since more than one beam may detect the cloud. Unfortunately, the referencing technique used, while providing remarkably flat baselines, will tend to remove correlated signals in adjacent beams, reducing the probability of detecting large-scale H_I discs in the nearer parts of the clusters.

The H_I mass range of 10⁶–10¹¹ h⁻² M☉ in Fornax and 3.5 x 10⁶ – 3.5 x 10¹¹ h⁻² M☉ in Centaurus allows the detection of progenitors of galaxies at least the size of the Milky Way, and any gas clouds with H_I masses like that of the ring in the Leo group (10⁶ M☉, Schneider et al. 1983) and the Virgo protogalaxy (4 x 10⁶ M☉, Giovanelli & Haynes 1989) would certainly have been detected in our survey of Fornax. Our zero detection of discrete intergalactic H_I clouds in the Centaurus and Fornax groups concurs with the results of a similar search in the Sculptor group (Haynes & Roberts 1979) which ruled out the existence of a significant population of non-optical H_I clouds with H_I masses greater than 10⁸ M☉, as well as the results of a void search (Krumm & Brosch 1984).

5.2 The cosmological significance of H_I clouds in the local Universe

The limit on Ω_H_I in the Eridanus cluster is weak owing to the very small survey volume of less than 3 h⁻³ Mpc³. In contrast, the large volumes that we have surveyed surrounding the Centaurus and Fornax clusters enable strong limits to be placed on Ω_H_I in cluster and near-cluster environments. The contribution of H_I in extremely low surface brightness objects to the cosmological density parameter for both Centaurus and Fornax is 99 per cent likely to be less than 10⁻² h⁻¹ for galaxies with H_I velocity widths of about 100 km s⁻¹, in agreement with previous results (Lo & Sargent 1979; Fisher & Tully 1981; Krumm & Brosch 1984). Note that most previous studies select a 95 per cent confidence limit.

Studies of damped Lyman α systems can also be used to constrain the cosmological mass density in H_I gas. Recent studies include those of Storrie-Lombardi et al. (1994) and Storrie-Lombardi, McMahon & Irwin (1996). The latter study places an upper limit of 5 x 10⁻⁴ h⁻¹ on the cosmological mass density in neutral hydrogen gas contributed by Lyα absorbers for 0.008 < z < 1.5. With corrections for possible dust obscuration, and neutral gas not residing in damped Lyα systems, this upper limit rises to 10⁻³ h⁻¹, consistent with our results.

ACKNOWLEDGMENTS

We thank Jason Contarini, Euan Troup, Warwick Wilson, Alan Wright, Margaret Mazzolari and Anthony Howes for helping with the observations at Parkes, and Virginia Kilborn for helping with the observations at the ATCA. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration. This research has also made use of the Digitized Sky Survey (DSS) provided by the Space Telescope Science Institute, based on photographic data from the UK Schmidt Telescope. DGB acknowledges the support of an Australian Postgraduate Award.

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