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21 cm Searches for Dim Galaxies

Mike Disney[1] and Gareth Banks[1,2]

[1] University of Wales College of Cardiff, PO Box 913, Cardiff CF2 5YB, UK
mjd@astro.cf.ac.uk, gdb@astro.cf.ac.uk

[2] Australia Telescope National Facility, CSIRO, PO Box 76, Epping 2121, Australia

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Abstract: We review very strong selection effects which operate against the detection of dim (i.e. low surface brightness) galaxies. The Parkes multibeam instrument offers a wonderful opportunity to turn up new populations of such galaxies. However, to explore the newly accessible parameter space, it will be necessary to survey both a very deep patch (10^5 s/pointing, limiting $N_{\rm HI} \sim 10^{18}$ cm^{-2}) and a deep patch (10^4 s/pointing, limiting $N_{\rm HI} \sim 3 \times 10^{18}$ cm^{-2}) in carefully selected areas, and we outline the case to do this.

Keywords: galaxies: general — galaxies: luminosity function — galaxies: mass function — galaxies: statistics

1 Introduction

Occham's Razor puts the astronomer into an uncomfortable quandry. It tells us 'if you can't detect something, then assume it's not there'. But given our limited technical capabilities, the Universe may well be filled, even dominated, by objects we cannot presently see.

We live inside the spiral arm of a comparatively high surface brightness galaxy ourselves, so the sky is bound to be relatively bright. On a dark night at a good observing site only 1 per cent of the light from the darkest parts of the sky is coming from beyond our Galaxy. All objects that are dimmer (i.e. lower in SB) than the terrestrial glare will be difficult to detect. And even when they are detected the accurate measurement of the true sizes and luminosities against the glare will be very uncertain. At the moment optical astronomers have only a very hazy idea about the true population of dim (low SB) galaxies. The largest fair sample of spirals we could muster contained only 65 members! Too much dogmatism is therefore out of place. One can currently conjecture that *'The great majority of galaxies, even in our neighbourhood, remain to be found.'*

2 Surface Brightness of Galaxies

Freeman (1970) pointed out that disk galaxies appear to have a remarkably uniform surface brightness of around $21{\cdot}65 \pm 0{\cdot}3B\mu$, or blue magnitudes per square arcsecond. [Surface brightness values, unless specifically mentioned, will be quoted as the extrapolated central SB measured by fitting a de Vaucouleurs (1959) profile, either exponential or 'r to the quarter'.] Disney (1976) then noticed that all of Fish's (1964) early photometry of ellipticals could also be explained if they too had a uniform SB of $14{\cdot}8 \pm 0{\cdot}9B\mu$. He further argued that both uniformities could be explained as a selection effect, because galaxies of the two types with precisely these SBs would have the largest isophotal apparent sizes when seen against the terrestrial sky with a photographic emulsion. He further speculated (1980) that some apparent dwarfs would turn out to be the central parts of much larger galaxies, which he dubbed 'Icebergs' or 'Crouching Giants' (being a giant Iceberg previously catalogued as a dwarf), whose outer parts would be apparently lost below the terrestrial sky. This speculation was dramatically confirmed by the serendipitous discovery by Bothun et al. (1987) of an apparent dwarf in Virgo that was in fact 25 times further away and therefore a 'Crouching Giant' of the most spectacular kind.

Since then there have been steady advances. Deeper analysis of the selection effects by Disney & Phillipps (1983) showed that when both isophotal size *and* isophotal magnitude are taken into account the surface-brightness selection effects are even more dramatic than earlier supposed. Every optical survey for galaxies must contain two limits: a faintest apparent magnitude and a smallest apparent angular size (both limits being isophotal) for any object included in the survey. These two limits can be combined to yield a single surface brightness referred to as the 'catalogue surface brightness' μ(cat). The 'visibility' of a galaxy, that is to say the volume within which it can lie and still be detected by the survey, is then a sensitive function of its own surface brightness $\overline{\mu}$ compared to μ(cat). Disk galaxies more than one magnitude dimmer than μ(cat) have very low visibilities because they are too large and therefore too much of their light is lost below the sky.

Disks with SBs more than one magnitude brighter than μ(cat) have very low visibilities because they are, at a given luminosity, too small to be included in the catalogue when any distance away. On the observational front, plate measuring machines and wider angle CCDs have allowed the detection of many more lower SB galaxies (e.g. Davies et al. 1988; Phillipps et al. 1987; Schombert et al. 1992; Sprayberry et al. 1995*a* 1995*b*; Turner et al. 1993; de Jong 1995). The upshot seems to be that as one surveys to fainter and fainter SB levels there are equal numbers of galaxies found in each one magnitude of SB between 21 and about 26·5 (Turner et al. 1993; McGaugh 1996); a remarkable result!

To the selection effects we must add the extreme difficulty of measuring distances in the optical for low SB galaxies. One needs then to resort to 21 cm techniques. But if one has to do that in the end, why not start with a 21 cm survey in the first place? It may prove to be the best and indeed the only way to delineate the population of dim galaxies.

3 21 cm Observations of Dim Galaxies

Immediately following our original conjecture (Disney 1976), Shostak (1977) looked back at existing 21 cm observations of optical galaxies to see if any 'Iceberg galaxies' had turned up accidently in the 'off-beams'. Out of several thousand observations there was not a single convincing 'Iceberg', and this was felt, at the time, to be a very telling argument against the existence of any extensive population of dim galaxies. This inference rested, however, on the implicit assumption that dim galaxies would have neutral hydrogen columns as high as 'normal' optical galaxies. But surely this is unreasonable? Dimness presumably corresponds to low surface density, and therefore to low hydrogen columns even in galaxies with normal $M_{\rm HI}/L_{\rm B}$ ratios (the total H I mass to optical B-band luminosity ratio).

The point can be made as follows. Starting from the antenna equation as usual, one can show that for an H I source of solid angle $\Delta\Omega_{\rm source}$ to be detected with S/N ratio $\sigma_{\rm rms}$, one requires it to have a column density,

$$N_{\rm HI} > \left[\frac{\Omega_{\rm beam}}{(\Delta\Omega)_{\rm source}}\right] \times 2\times 10^{16} K\sigma_{\rm rms} T_{\rm s} \times \sqrt{\frac{\Delta V(\rm km\,s^{-1})}{t_{\rm obs}(s)}}\,, \qquad (1)$$

where K is a numerical factor of order unity, $T_{\rm s}$ is the system temperature, $\Omega_{\rm beam}$ is the solid angle subtended by the beam, ΔV is the velocity dispersion of the gas, and $t_{\rm obs}$ the integration time.

For sources smaller than the beam, this converts to the usual

$$(M_{\rm HI})_\odot > 5\times 10^9 \frac{r^2_{\rm Mpc}}{D^2_{\rm M}} \sqrt{\frac{\Delta V(\rm km\,s^{-1})}{t_{\rm obs}(s)}} M_\odot\,, \quad (2)$$

where we have taken $\sigma_{\rm rms}=5$, $K=2\sqrt{3}$ (Rohlfs 1986), $T_s = 40$ K, $D_{\rm M}$ is the size of the telescope in metres and $r_{\rm Mpc}$ is the distance to the source. This can be converted to yield the maximum range for detection:

$$r^2_{\rm Mpc} < 2\times 10^{-10} \frac{(M_{\rm HI})_\odot D^2_{\rm M}\, t^{0\cdot5}_{\rm obs}}{\sqrt{\Delta V(\rm km\,s^{-1})}}\,, \qquad (3)$$

so that the range $r \propto t^{0\cdot25}_{\rm obs}$, and hence the volume searched varies as $r^3 \sim t^{0\cdot75}_{\rm obs}$. Thus in a blind survey the number of sources $O(t)$ detected, in observing time $t_{\rm obs}$, in a fixed direction, goes as $\delta O/O = \frac{3}{4}\delta t_{\rm obs}/t_{\rm obs}$

Since $O(t)$ does not rise as fast as $t_{\rm obs}$, observers with a total time T to spend on a survey have generally made short integrations in order to cover a large area of sky and so to maximise $O(t)$.

Now consider the other limit, i.e. for sources larger than the beam: (1) then converts to

$$N_{\rm HI} > 10^{18}.T_{\rm s}\sqrt{\frac{\Delta V(\rm km\,s^{-1})}{t_{\rm obs}(s)}} \qquad (4)$$

(where we have taken $K\sigma_{\rm rms} \equiv 20$, following tests at Jodrell Bank). This shows that radio telescopes have surface intensity limits *independent of their size*. (The size drops out because larger telescopes have smaller beams and hence see less hydrogen from a given extended source.) Because at 21 cm astronomers have rarely used integrations beyond 30 minutes *almost nothing is known of the extragalactic world below* $N_{\rm HI} \sim 10^{19}$ cm^{-2}. According to Briggs (1990), 'the short integration times that typify 21 cm line redshift surveys could not reliably detect $N_{\rm HI}$'s much less than 10^{20} cm^{-2}, even if the emission filled the beam.'

Now consider galaxies. Because an SB of 27 $B\mu \sim 1$ $(L_\odot)_{\rm B}$/pc^2, one can show that

$$N_{\rm HI}\,({\rm cm^{-2}}) \sim 10^{20}\,(M_{\rm HI}/L_{\rm B})\,10^{(0\cdot4(27-\mu_{\rm B}))}\,, \quad (5)$$

where $\mu_{\rm B}$ is a mean SB over the hydrogen-bearing area. Adjusting (5) for the fact that hydrogen radii are generally larger than optical ones, we obtain the correspondence between mean surface brightness and column density shown in Table 1.

Table 1. Surface brightness ($B\mu$) versus column density (atoms cm^{-2}) for different values of $M_{\rm HI}/L_{\rm B}$

$N_{\rm HI}$ (cm^{-2})	$(M_{\rm HI})_\odot/(L_{\rm B})_\odot$ 0·1	0·2	0·4	1	4
10^{21}	21·35*	22·5*	23·25*	24·25*	25·75**
$4{\times}10^{20}$	22·75*	23·5*	24·25*	25·25**	26·75**
10^{20}	24·25*	25·0*	25·75**	26·75**	28·25
$4{\times}10^{19}$	25·25*	26·0**	26·75**	27·75	29·25
10^{19}	26·75**	27·5	28·25	29·25	30·75
$4{\times}10^{18}$	27·75	28·5	29·25	30·25	31·75
10^{18}	29·25	30·0	30·75	31·75	33·25

* visible on POSS ** visible on UK Schmidt

Three conclusions can immediately be drawn from the table:

(1) Existing 21 cm surveys, capable of reaching not far below $N_{\rm HI} \sim 10^{20}$ cm^{-2}, set no intensity constraints on the population of low SB and invisible galaxies. Any galaxy they can detect should be visible on existing Schmidt surveys. For instance, Shostak's observations were far too short to pick up 'Iceberg' galaxies. The 'Crouching Giant' Malin 1 was picked up so easily at 21 cm only because of its uniquely high $M_{\rm HI}/L_{\rm B} \sim 5$. Most such Crouching Giants may have 'normal' $M_{\rm HI}/L_{\rm B}$ values 10 times lower, and would be far harder to detect at 21 cm.

(2) An all-sky multibeam survey with short ($<10^3$ s) integrations per pointing will pick up optically undetected galaxies only if they have $(M_{\rm HI}/L_{\rm B})_\odot$ of 4 or more.

(3) However, were it possible to reach column densities as low as 10^{18} cm^{-2}, a new region of parameter space would open up, a region which may contain numerous galaxies too dim to be picked up on either existing optical or indeed 21 cm surveys.

4 Surveying a Very Deep Patch

Taking up the last point, could we, with a multibeam instrument, survey a limited piece of sky to sufficient depth either to find, or to rule out, a cosmologically interestingly population of dim or dark galaxies? According to equation (4), it takes $t_{\rm obs} \sim (10^{18}/N_{\rm HI})^2 T_s^2 \Delta V \sim 1 \times 1000 \times \Delta V ({\rm km\,s^{-1}}) \sim 24$ hours to reach 10^{18} cm^{-2}.

The maximum distance $d_{\rm max}$ to which one could see such dim galaxies would correspond to that at which they would fill the beam (size β in radians), in which case with the $N_{\rm b}$ beams of a multibeam survey, one would survey a total volume $V_{\rm max}$ *per pointing* of

$$V_{\rm max} = 1\cdot 8 \times 10^{12} \left(\frac{N_{\rm b}}{\beta}\right) \times \left[\frac{(M_{\rm HI}/L_{\rm B})(L_\odot)_{\rm B}}{N_{\rm HI}({\rm cm^{-2}})}\right]^{1\cdot 5} {\rm Mpc}^3. \quad (6)$$

Such a volume (Parkes) would contain $\sim$10 normal, i.e. high SB, Schecter (1976) L^* galaxies. If, therefore, we made 10 such $\sim$24$^{\rm h}$ pointings, we ought to pick up $\sim$100 normal L^* galaxies and a number $N_{\rm dim}$ of dim (i.e. 10^{18} cm^{-2}) L^* galaxies such that

$$\frac{N_{\rm dim}}{100} \sim \frac{\Omega_{({\rm dim}L^*{\rm galaxies})}}{\Omega_{({\rm normal}L^*{\rm galaxies})}}, \quad (7)$$

where the Ω's refer to their relative contribution to the cosmic density parameter, Ω.

It follows that in a program of only 10 pointings, each lasting between 24$^{\rm h}$ and $3 \times 24^{\rm h}$, the Parkes multibeam system will either pick up a healthy sample of an entirely new population of 'Iceberg galaxies', or else rule them out, once and for all, as significant (i.e. >10%) contributors to the cosmic density of all galaxies. Either way, this would be such an important result that we simply have to do it.

It has been postulated that all disk galaxies will have a sharp cutoff at $N_{\rm HI} \sim$ a few $\times 10^{19}$ cm^{-2}, at which point the conversion of atomic into ionised hydrogen occurs. The explanation for this could lie with internal or external ionising photons, and in particular the cosmic UV background. Two galaxies have been used to check for this abrupt cut-off (or 'sharp edge') to the H I disk. Van Gorkom (1993) used the VLA to verify this characteristic in NGC 3198, by undertaking a 100 hour integration, reaching a sensitivity corresponding to $N_{\rm HI} \sim 4 \times 10^{18}$ cm^{-2}. The sharp outer edge was observed to occur at $N_{\rm HI} \sim$ a few $\times 10^{19}$cm^{-2}. Corbelli, Schneider & Salpeter (1989) corroborated this by performing a sensitive scan along the major axis of M33, the largest galaxy in angular extent that can be observed with Arecibo, and finding a cutoff at $N_{\rm HI} \sim 3 \times 10^{19}$ cm^{-2}. To further substantiate these findings, Maloney (1993), Corbelli & Salpeter (1993), and Dove & Schull (1994) applied photoionisation models to these two galaxies and predicted the observed edges. Note, however, that the intergalactic radiation field is likely to vary considerably between, say, the inside of a spiral-rich cluster and a void. More cogently, there appears to be no break at $N_{\rm HI} \sim 10^{19}$ cm^{-2} in the number density of QSOALs as a function of $N_{\rm HI}$, which runs smoothly down, all the way from 10^{21} cm^{-2} to 10^{13} cm^{-2} (Tytler 1987) as $N_{\rm HI}^{-1\cdot 5}$. More recently, Corbelli & Salpeter (1997) have repeated the work on M33 to show that the effects of disk inclination affect earlier interpretations of the sharp fall-off in H I column density. Their observations, to the northwest and southeast of M33, render them incapable of excluding a faint level of H I, possibly of $N_{\rm HI} \sim 6 - 8 \times 10^{18}$ cm^{-2}, although this may well be caused by distant sidelobe contamination. In short, there is currently little observational evidence to indicate that hydrogen columns below $N_{\rm HI} \sim$ a few $\times 10^{19}\,{\rm cm}^{-2}$ should cease to exist.

John Dickey's (1997) observations of the Hercules complex show how localised the neutral hydrogen may be. In the dense, X-ray emitting regions, all the H I appears to have vanished, whereas in the spiral-rich region he finds numerous patches associated with either very dim, or in some cases apparently invisible, galaxies. This phenomenon, which he refers to as the 'Massacre of the Innocents', poses a real challenge for Deep Patch enthusiasts. Where should we point the telescope?

5 Discussion

Thus far 21 cm surveys have been bedevilled by short integrations. To complete half the sky in a couple of years will force integration times per pointing of less than 1000 s, with the danger of missing the most interesting sources, such as intergalactic hydrogen clouds. The way around this is to have three surveys going on concurrently: a shallow all-sky survey with $t_{\rm obs} \sim$ 500–1000 s, a Very Deep Patch with $t_{\rm obs} \sim 24^{\rm h}$ (Section 4), and an Intermediate Deep Patch of around 100 pointings, each of around 10^4 s, aimed say in Sculptor where there is already known to be a lot of H I. Hopefully, we then won't miss very much.

Finally, it is worth reminding ourselves that the Universe is dominated by dark matter. Were it otherwise, then the Iceberg galaxies which we hope to find would probably all have been torn apart. But dim galaxies are not necessarily light galaxies. Malin 1 has a $350\,{\rm km\,s}^{-1}$ wide rotation curve (W_{20}). The exciting work of de Blok et al. (1996), who have measured the rotation curves of a number of moderately dim galaxies, shows that their mass-to-light ratios rise systematically as their SBs fall. Combining this with the recent discovery (Bergeron 1997) that dim and dwarf galaxies may be the absorbers responsible for QSOALs, it may yet turn out that dim galaxies contain most of the galaxy mass (and light) in the cosmos. The multibeam surveys at Parkes and Jodrell Bank will probably find out.

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