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The H I Luminosity Function from 'Blind' Surveys

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Abstract: Recent neutral hydrogen (H I) surveys have detected enough sources to make initial predictions of the extragalactic H I luminosity function. These surveys provide useful pointers for the Parkes Multibeam Survey, highlighting various advantages and disadvantages of different observing and analysis procedures. The newest surveys are also large enough to permit some statistical tests of their completeness. The detection rates clearly fall short of what would be expected based on a simple propagation of errors, suggesting the need for further development of detection software. I suggest several procedures for determining the effective sensitivity of H I surveys. Applied to two recent Arecibo surveys, these suggest that the H I luminosity function may be much steeper than its optical counterpart, and that the Parkes surveys may detect a large number of low-mass sources.

Keywords: radio lines: galaxies — galaxies: mass function

1 Introduction

The 21 cm line of neutral hydrogen gives us almost our only view of galaxies that is independent of stars. Stars directly generate nearly all of the visible emission, of course, and they are also directly or indirectly responsible for almost all of the emission at other wavelengths. For example, far-infrared emission from interstellar dust grains is powered by starlight heating the grains, and the grains would not exist but for the nucleosynthesis in former generations of stars. Likewise, virtually every other form of continuum or line radiation is powered by stars in some stage of their evolution and/or depends on the byproducts of stellar evolution. By contrast, neutral hydrogen is primordial, and the 21 cm line has such a low excitation temperature that the ionising extragalactic background radiation is sufficient to maintain its excitation.

Until recently, 21 cm receivers were not sensitive enough to easily detect the H I line from galaxies. Since a large investment of time was needed to detect a galaxy, observers pointed their radio telescopes at known galaxies — known from their optical emission. Unfortunately, this teaches us little about H I independent of stars. In recent years, system temperatures have improved to the point that a galaxy could be detected rapidly, often in as little as a few seconds. Coupled with the advent of large multi-beam systems like the 13-beam Parkes receiver, it has become feasible to start surveying the sky 'blindly' to determine how neutral hydrogen behaves in its own right.

Several single-beam surveys at Arecibo, Green Bank, the VLA, and smaller telescopes have been and are currently being conducted. The Parkes Multibeam Survey will surpass all of these surveys combined, as it examines an entire hemisphere of the sky. The multibeam receiver should provide the ideal equipment for a blind survey, with good sensitivity and the potential for excellent interference rejection by cross-comparison of the signals.

My focus in this paper will be on the steps needed to translate H I survey observations into a galaxy luminosity function. I apply tools developed for understanding the completeness of optical samples to two Arecibo surveys, and discuss some of the problems associated with interpreting the results. These problems suggest that we need a much more thorough understanding of how observing procedures and line-identification techniques impact on the detection rate, and I suggest some strategies for the Parkes survey and analysis procedures to clarify the interpretation.

2 The Mass/Volume Sensitivity Function

The mass/volume sensitivity function characterises H I surveys according to the total volume in which a survey can detect a galaxy of a given mass. It is usually based on simple assumptions about the line shapes of galaxies and the effects of noise. I will argue later that this description is insufficient to generate an accurate luminosity function, but it is a useful starting point.

Table 1. Major 'blind' extragalactic H I surveys

Survey	Velocity range ($km s^{-1}$)	Beam FWHM (arcmin)	Number of Points	Δv ($km s^{-1}$)	σ (mJy)
Shostak (1977)	−400–1422	10·8	~3100	11	32
	−800–2835	10·8	~2500	11	44
Fisher & Tully (1981)	−300–1300	10·8	770	22	13
	−300–3000	10·8	970	22	18
Krumm & Brosch (1984)	6300–9600	10·8	~1400	45	20
	5300–8500	10·8	~1800	45	20
Henning (1992)	300–7500	10·8	4000	22	8
	−400–6800	10·8	3204	22	8
Weinberg et al. (1991)	4500–5700	30	12	40	0·4
	2650–3850	30	30	40	1
Sorar (1994)	−700–7400	3·3	~5000	16	0·8
	−700–7400	3·3	~10000	16	4
Spitzak (1996)	100–8340	3·3	14130	16	1·9
Arecibo Dual-Feed[1]	−650–7980	3·3	~170000	32	3
Parkes Southern Survey[2]	−760–12170	14·4	~419000	13	~4
Parkes ZoA Survey[2]	−760–12170	14·4	11000	13	~2

[1] Schneider (in progress) [2] Staveley-Smith (1997)

Consider a galaxy with an H I mass $M_{\rm HI}$ (in solar masses). Rotation of the galaxy (and to a much lesser extent turbulence) will Doppler-broaden the H I line to a width w ($km s^{-1}$). For all practical purposes the 21 cm line is optically thin and its emission strength is independent of temperature, so the integrated power in the line is directly proportional to the total mass of H I. If this galaxy is at a distance D (Mpc), its integrated emission is

$$S_{\rm HI} \times w = 4{\cdot}24 \times 10^{-3} M_{\rm HI}/D^2\,, \qquad (1)$$

where $S_{\rm HI}$ is the mean flux density (in mJy) within the line profile. I will use distances based on $H_0 = 75$ $km s^{-1}$ Mpc^{-1} throughout to translate from redshifts to distances.

This flux must be detected against a noise arising from the receiver and background emission. If the spectrum has a velocity resolution of Δv (in $km s^{-1}$), the noise can be reduced by averaging or 'smoothing' the spectrum to a lower resolution, with the noise improving as $(\Delta v)^{-1/2}$. However, if the smoothing is too great, the line itself is averaged with the background; the best result is achieved when the smoothing just equals the linewidth. Starting with a spectrum having a measured rms noise σ (at the resolution Δv), and smoothing it to a resolution matching the galaxy linewidth gives a signal-to-noise ratio of

$$S_{\rm HI}/N = 4{\cdot}24 \times 10^{-3} \frac{M_{\rm HI}}{wD^2} \times \frac{\sqrt{w/\Delta v}}{\sigma}\,. \qquad (2)$$

More realistically, the 21 cm spectrum should allow the line to be detected over several resolution elements to identify a signal, so this signal-to-noise ratio is not achieved in practice. We must also contend with occasional large noise fluctuations, baseline irregularities, imperfect pointing, and interference. Given these problems and the extra free parameter introduced by searching over a range of linewidths, it is not certain how much advantage is gained by smoothing. However, if we simply require the nominal smoothed signal-to-noise ratio to be >5, the maximum distance to which a galaxy could be detected is

$$D_{\rm max} = 2{\cdot}91 \times 10^{-2} \left(\frac{M_{\rm HI}}{\sigma\sqrt{w\Delta v}}\right)^{\frac{1}{2}} \qquad (3)$$

in Mpc, for a mass in solar masses, σ in mJy, and velocities in $km s^{-1}$. Of course, the maximum distance is limited by the observed bandpass if it does not reach as high a redshift as this distance implies.

To determine the survey volume, we also need the survey area. Radio telescopes have beam diameters approximately inversely proportional to the telescope diameter d, so larger telescopes require about d^2 more observations to cover the same area. For unresolved sources the integration time needed to reach a given flux sensitivity goes as d^{-4}, while for resolved sources the integration time goes as d^{-2}. Therefore, the time required to observe the same area of the sky to the same depth is inversely proportional to the square of the telescope diameter for unresolved sources and approximately the same for resolved sources (ignoring time spent moving the telescope, etc.). Because larger-telescope surveys have normally taken advantage of the d^{-4} sensitivity dependence for unresolved sources to cut their integration times and cover more area, one special niche the Parkes surveys can fill is through their sensitivity to very extended, low surface brightness H I emission.

The distance sensitivity also depends on where the source is within the beam. In fact some surveys (Sorar 1994) have used sidelobes as a further probe

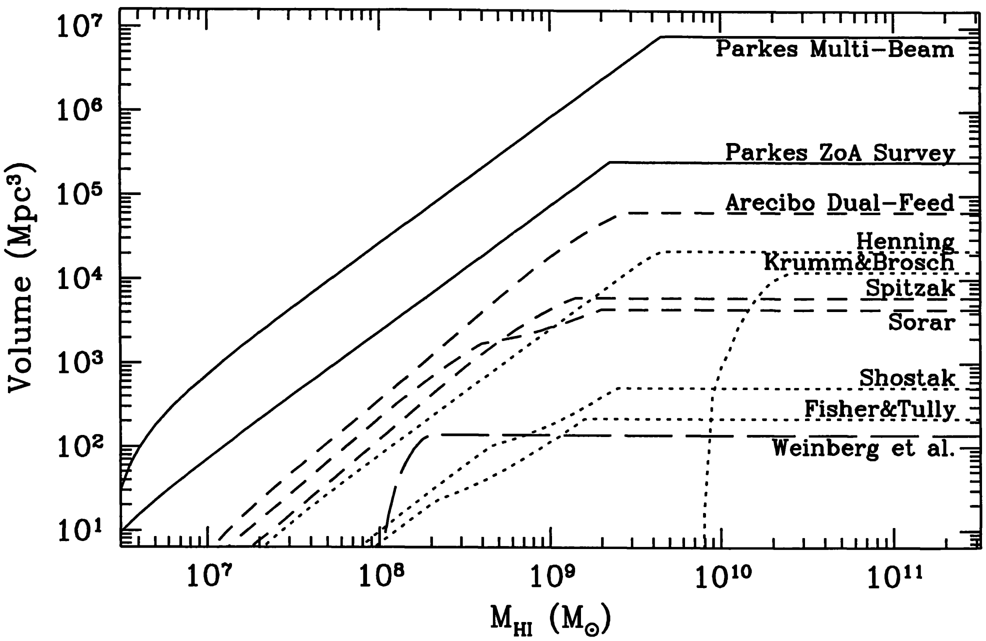

Figure 1—The volume/mass-sensitivity relationships of major H I surveys listed in Table 1. The curves show the total volume within which each survey would have been sensitive to a hypothetical galaxy with a linewidth of 100 km s^{-1} of the given H I mass. Green Bank surveys are shown by dotted lines, Arecibo by short dashes, VLA by long dashes, and Parkes by solid lines.

of lower sensitivity but larger area. For comparison's sake, I ignore sidelobes and suppose that the beam is uniform within the half-power beam width. I also do not correct here for how the relative sensitivity as a function of offset from beam centre (see, for example, Shostak 1977) reduces the volume sensitivity. Depending on the amount of overlap between observations, the effective volume searched may be only half of what is quoted here. Thus surveys that are more contiguous and have more uniform integrated sensitivities, as is planned for the Parkes surveys, can have a significantly better volume sensitivity than a simple comparison indicates.

Table 1 lists the vital statistics for several recent H I surveys along with a set of projected values for the Parkes Multibeam Surveys (Staveley-Smith 1997, present issue p. 111). The velocity range and beam size are listed in columns 2 and 3. There are two entries for surveys that covered two velocity ranges. Not all of the necessary data were always included, but I have attempted to place all the surveys on a common scale. Thus, surveys carried out in drift-scan mode are given a number of observation points (column 4) that would generate an equivalent search area, and the integration time and spectral resolution (column 5) were sometimes used to estimate rms noise levels (column 6). Arecibo noise values are based on an average of the frequency-dependent noise across the spectra.

The corresponding volume sensitivities for different H I masses are shown in Figure 1. I assume a galaxy with a linewidth of 100 km s^{-1}, which is reasonable for the lower H I masses; at higher masses, the effective search volumes would be smaller than shown. For the volume calculations I also limit the minimum redshift to >300 km s^{-1}, because of confusion with high-velocity clouds in the Milky Way. Most of the curves show a characteristic (flux-limited) rise with mass as $M_{\rm HI}^{\frac{3}{2}}$ at low masses until a mass is reached to which the survey is sensitive at its maximum redshift. Surveys with high minimum redshifts (Weinberg et al. 1991; Krumm & Brosch 1984) have a sharp cutoff at low masses. The Arecibo surveys have a more complex sensitivity roll-off with frequency that steepens the curves slightly.

Many observers have pointed out that in the course of standard H I observations, calibration ('off') scans have been collected that could potentially represent an enormous survey volume. I limit consideration to the deliberate blind surveys because much more effort was put into these surveys to identify possible signals. Most observers, pressed by the exigencies of their particular project, dismiss small negative features in their spectra as interference because they are usually correct in this assumption. By contrast, the blind surveys devote most of their attention to identifying real signals and discriminating them from interference or other instrumental problems.

3 Survey Strategies

It is obvious from Figure 1 that the Parkes surveys will take us to a new level of sensitivity over the entire range of H I masses. What the curves do not show is how the strategies of these surveys also affect their results.

Many of the surveys were actually carried out in continuous scanning mode. These surveys can be identified by the tilde in front of the number of points in Table 1, which corresponds to the length of the survey strip divided by the beam width. Most of these surveys were done in drift-scan mode, which helps maintain more stable characteristics in the baselines. The Arecibo Dual-Feed survey (in preparation) further improved interference monitoring by using two 21 cm feeds simultaneously, and comparing the output in both polarisations and in the two feeds. These techniques are important for reducing the number of false signals in the surveys.

The Parkes Surveys will have 12 comparison dual-polarisation feeds, so that interference monitoring should be excellent. Baseline and standing-wave variations may be more problematic if the Southern Sky Survey is done in a driven scanning mode, and this problem may also arise in the Zone of Avoidance survey. In the Arecibo surveys, the Sun produced standing waves between the dish and feed platform that depended sensitively on the sun–dish–feed angles, reducing the survey effectiveness. In continuous scanning modes, however, a model of the standing waves can be generated if they change slowly enough (Briggs et al. 1997, present issue p. 37).

Spitzak (1996) used a 'step–stare' mode which achieves much the same effect as the continuous scanning mode. In addition, by 'leap-frogging' over points on the observing grid, it allowed interference monitoring by requiring that a potential signal not repeat over the short time interval between observations that were separated by large angular distances. Spitzak's survey is also the only deep survey to date that had essentially complete coverage over a large contiguous region. This will also be a feature of the Parkes surveys and is very helpful in determining the luminosity function since it is unnecessary to form complex models of the beam sensitivity for an uncertain displacement of the source from beam centre.

Also note that the VLA survey of Weinberg et al. (1991) at first appears comparable to the much earlier Green Bank surveys of Shostak (1977) and Fisher & Tully (1981). The volume limit on this survey was imposed mainly by limitations on bandwidth forced by 'back-end' correlators and computers. However, Weinberg et al. achieved a much higher spatial resolution than any of the other surveys: the $30'$ beam size refers to the primary beam—the synthesised beam was $\sim 45''$. They detected a surprisingly large number of low-mass objects within their small search volume: nine dwarfs, mostly companions to targeted bright galaxies. Large-beam surveys like the Parkes one would have trouble separating most of these objects from the larger neighbour. In the multibeam survey it will be especially important to achieve Nyquist spacing between beam positions or to tilt the array relative to the scan path in scanning mode to generate sub-beam spacing. This will provide information that should help in resolving source confusion. This is not an area that has been explored by earlier surveys, so I anticipate that a major component of the Parkes survey analysis will be the development of techniques to identify and distinguish confused sources.

4 Survey Sensitivities Achieved

Most H I surveys to date have quoted some sort of sensitivity based on the rms noise in their spectra, often along the lines of equation (3). A 5σ limit as suggested there sounds like a reasonable expectation, but all of the surveys have allowed various degrees of user intervention to reject 'unlikely' signals or to pick the best cases for follow-up. The simple 5σ limit also ignores subtle effects like baseline subtraction, which may mask signals. It is important to test the surveys in other ways to determine their actual sensitivity. The recent Arecibo surveys have detected large enough numbers of objects to carry out statistical tests on their level of completeness.

In Figure 2, the linewidths and observed fluxes of H I features detected by Sorar (1994) and Spitzak (1996) are plotted on scales in the same ratio as their rms baseline noise levels. The points for Sorar exclude objects that were detected in the sidelobe. The points for Spitzak include several objects undetected in the survey, but which had previously measured redshifts. The 5σ line appears to represent a fairly good lower bound on the detectable fluxes for both samples, even though the surveys were carried out and analysed in quite different fashions.

This is not the whole story, though. One would expect the number density of sources to increase rapidly as the limiting-flux line is approached; instead the number density seems to drop slightly near this limit. This could be because the H I surveys are volume-limited by their upper limiting redshifts, but it might also be caused by a roll-off in sensitivity near the flux limit. Note that because the fluxes here are 'as observed' this is distinct from the problem of sensitivity decline when sources are not at the beam centre. There are several methods of testing the actual survey sensitivity.

One probe of a survey's completeness is a $V/V_{\rm max}$ test. Each source has a limiting distance to which it can be detected, determined either by equation (3) or by the limiting redshift of the survey. On average, the distance to an object ought to be halfway into its detectable volume. Therefore, the volume in front of a detected source, $V \propto D^3$, should average half of the maximum possible volume in which the object *could* be detected: $V_{\rm max} \propto D^3_{\rm max}$.

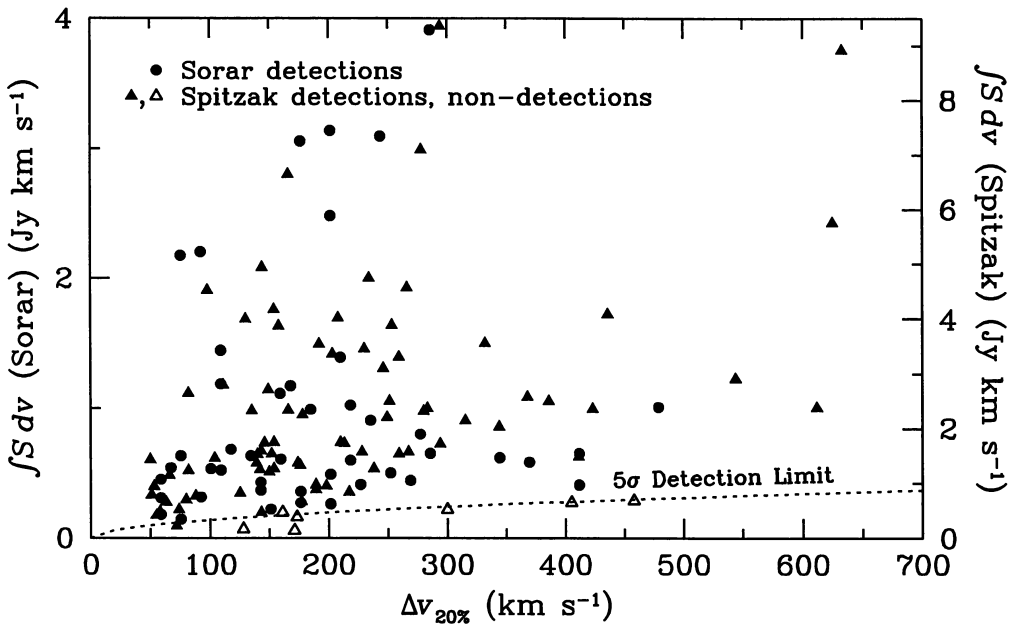

Figure 2—Observed fluxes versus linewidths of objects detected by Sorar (1994) and Spitzak (1996) relative to the 5σ width-dependent detection limit. In addition, known objects undetected by Spitzak, but measured in deeper integrations, are also shown with open triangles.

Both samples have average values of $V/V_{\rm max}$ of only 0·35, and both require an effective limiting flux about 70% higher than 5σ to give the correct mean of 0·5. Unfortunately, because of large-scale structure within the surveyed regions, this test is somewhat uncertain, although Sorar's survey covers nearly 24 hours in right ascension, so it should be less affected by local structures.

The roll-off in detections is also apparent in a second test, which is the analog of the optical $\log N$–$\log m$ test. We can define a 'relative H I magnitude' as $-2{\cdot}5\log$ (flux/minimum flux), where the minimum flux is based on the 5σ limit for the signal's linewidth. In subsets of the data which are nominally sensitivity limited, the distribution of counts should rise by a factor of 2 in each half-magnitude fainter bin, as is well-known optically. Both Spitzak's and Sorar's samples show the expected rise in number counts until the faintest half-magnitude bin above the nominal sensitivity limit where the counts *drop*. This indicates that several times fewer galaxies are being detected than should be within a factor of about two of the nominal 5σ limit.

These indications that H I signal detection procedures are not as effective as we think are a little disappointing, but hardly surprising. The nominal 5σ detection limits would only be attained for spectra that required no baseline fitting, were free of interference, and in which a single (smoothed) channel would be sufficient to declare a detection. Moreover, simply choosing a higher limit does not adequately describe the surveys' sensitivities since *some* objects are detected down to 5σ as seen in Figure 2.

For the best determination of the H I luminosity function, what is needed is a detailed knowledge of the sensitivity roll-off as a function of the H I linewidth. A method that we are employing in reducing the Arecibo dual-beam survey data is to introduce artificial H I signals close to our suspected sensitivity limit, ranging from the undetectable to the obvious. We generate these randomly all over the sky and over our entire bandpass range, with widths that span the full observed range of galaxies. These artificial sources are inserted into the raw data before any signal processing is attempted and then subjected to all of the baselining and interference filtering schemes we use. Our initial results suggest that we are even less sensitive to wide-profile sources than equation (3) implies. I would recommend a similar procedure for determining the sensitivity of the Parkes surveys.

5 The H I Luminosity Function

To conclude on a positive note, we can use the tests described in the last section to correct the number counts and generate an H I luminosity function. In Figure 3, I show the results obtained using Sorar's (1994) and Spitzak's (1996) data. The counts are corrected based on the $V/V_{\rm max}$ and relative H I magnitude tests described in the previous section, which imply a $\sim$2×poorer effective sensitivity than has been assumed in previous analyses of these data (Schneider 1996; Sorar 1994). In addition to simple

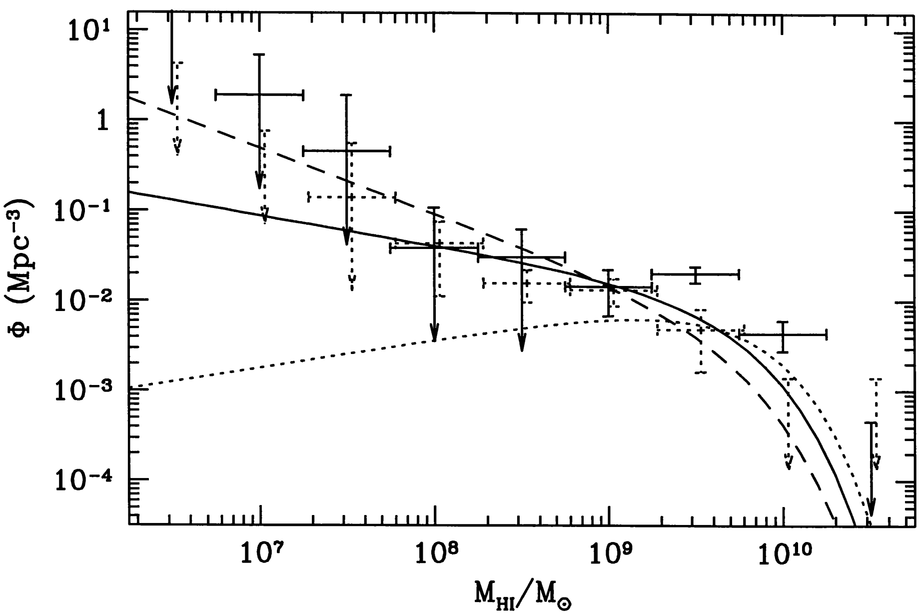

Figure 3—H I luminosity function based on two recent surveys. Sorar's (1994) data are shown with dotted crosses and Spitzak's (1996) data are shown with solid crosses. Schechter luminosity functions with $M_{\rm HI\star} = 7\times10^9 M_\odot$, and $\alpha = -0\cdot7$ (dotted line), $\alpha = -1\cdot32$ (solid line) and $\alpha = -1\cdot7$ (dashed line), are shown for comparison (see text).

$\sqrt{N}$ error bars, I have also included an uncertainty of ±2 to allow for small-number statistics and to estimate upper limits over mass ranges where no objects were detected. Note that the masses of Sorar's objects may be underestimated by a factor as large as 3–5 because of an unknown offset of up to ~3 arcmin from the scan centre for these 'main-beam' detections. Nevertheless there is good agreement between the two data sets.

It appears that there may be a very high space density of low-mass, H I-selected objects. A Schechter luminosity function (Schechter 1976) with a power law as steep as $\alpha = -1\cdot7$ (with $M_{\rm HI\star} = 7\times10^9 M_\odot$), as suggested by Impey, Bothun & Malin (1988), is consistent with the data, as shown by the dashed line in Figure 3. Such a steep function would spread the integrated H I mass almost equally across logarithmic intervals from the dwarfs to giants (Briggs 1990). However, a much shallower power law, like the $\alpha = -0\cdot7$ optical luminosity function derived by Lin et al. (1996; dotted line), is difficult to completely rule out because of the small-number statistics of these two surveys. Note that the dotted line uses the same normalisation as Lin et al., but with the same value of $M_{\rm HI\star}$ as above, so there may be up to four orders of magnitude difference in the counts at the faint end for an H I- as opposed to an optical-selected sample of galaxies.

Finally, although the small number of objects under consideration do not perhaps warrant much further analysis, I have applied a maximum-likelihood method like that of Sandage, Tammann, & Yahil (1979) to estimate the best-fit parameters of the luminosity function. The method was modified to account for the uncertainty in the beam offsets in Sorar's data. Because the results were so sensitive to the nature of the sensitivity roll-off, I limited the sample to detections brighter than about 20σ, where the data should be complete. Both Spitzak's and Sorar's samples then gave consistent values of $\alpha = -1\cdot32$ and $M_{\rm HI\star} = 7\times10^9 M_\odot$. This is shown as a solid curve in Figure 3.

These results suggest that the H I luminosity function may be much steeper than its optical counterpart, but they await a much bigger survey for confirmation. Given the various values of α examined here, the Parkes Multibeam surveys may detect thousands or only a few objects with masses $M_{\rm HI} < 10^7 M_\odot$. If the maximum-likelihood fit is correct, this number will be about a hundred. With this large range of outcomes, there should be little concern about small-number statistics dominating the uncertainties as they have in the Arecibo surveys. However, the Parkes surveys will be faced with the challenge of discriminating low-mass objects from the larger galaxies that will frequently accompany them. The Parkes surveys will also be able to determine whether the H I luminosity function drops off like the optical distribution function at high masses or if it has its own distinctive behaviour. The challenge here will be to develop better algorithms for identifying wide-profile sources in the presence of baseline instabilities. Having answered these challenges, the Parkes surveys should provide us with a firm grasp on the shape of the H I luminosity function along with its implications for the nature of extragalactic populations.

Acknowledgments

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