The Tail of the HI Mass Function

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Abstract. The contribution of extragalactic objects with HI masses below $10^8 M_\odot$ to the HI mass function remains uncertain. Several aspects of the detection of low-mass sources in HI surveys are not always considered, and as a result different analysis techniques yield widely different estimates for their number density. It is suggested at one extreme that the number density of galaxies follows a shallow Schechter power-law slope, and at the other extreme that it follows a steep faint-end rise like that found for field optical sources. Here we examine a variety of selection effects, issues of completeness, and consequences of LSS. We derive results for the large Arecibo Dual Beam Survey which indicate that the field mass function does rise steeply, while within the Virgo Cluster environs, the slope appears to be much shallower. Dependence on the local density of galaxies may partially explain differences between surveys.

1. Introduction

The shape of the HI mass function, particularly the behavior below $10^8 M_\odot$, has been the subject of considerable controversy. As paramaterized by a Schechter function slope $\alpha$, several studies seem to indicate a fairly shallow slope of $\alpha \approx -1.2$, including the HI masses of: optically-selected samples (e.g., Briggs & Rao 1993; Huchtmeier, this volume); galaxies in high-density regions like the Canes Venatici group (Kraan-Korteweg et al. 1999), Centaurus A (Banks et al. 1999), and the Ursa Major cluster (Verheijen et al. this volume); even some “blind” (optically unbiased) surveys.

On the other hand, several studies suggest the slope may be considerably steeper in field samples. Initial reports at this meeting of results from the Parkes survey suggest a slope of $\alpha = -1.5$ (Webster et al. this volume). Interestingly, Kraan-Korteweg et al. (1999) found $\alpha = -1.4$ when they did not restrict their sample to the Canes Venatici group. Our analysis of two earlier Arecibo surveys (Schneider et al. 1998; SSR hereafter) also suggested a steeper slope or a faint-end rise similar to the rise found for an optical sample of field objects found by Loveday (1997) and Driver & Phillipps (1996).

There are several possible causes for different conclusions to be drawn about the population of low-mass HI sources. Some of these have to do with astrophysical characteristics of the sample, like the effects of LSS and distance uncertainties. However, a significant cause of the differences is analysis problems:
(1) a poor understanding of survey sensitivity; (2) small number statistics; and
(3) selection effects.

To address these problems, we have completed the largest blind HI survey
to date at the Arecibo Observatory. The Arecibo Dual-Beam Survey (ADBS;
Rosenberg & Schneider 2000 and this volume) covers 430 sq. deg. in drift
scans at 30 separate declinations between $9^\circ < \delta < 28^\circ$. We were able to
achieve an rms sensitivity of 3-4 mJy per 3.3 arcmin beam along the drift scans.
We also repeated most of the scans to provide internal confirmation of source
detections. The advantages of using Arecibo for this type of survey are discussed
by Rosenberg & Schneider (2000).

The most important new feature of the ADBS is the insertion of hundreds of
“synthetic” HI signals prior to applying the data reduction procedures. These
sources allow us to test our actual sensitivity and completeness directly. We
discuss these issues in detail in §2. The resulting mass function for the field
population of galaxies in the ADBS is derived in §3.

Large-scale structure (LSS) may also have an effect on the shape of the
mass function. Density differences also affect the derivation of the mass func-
tion, as do large scale flows and velocity dispersion relative to the Hubble flow.
We examine these potential effects in §4. Our analysis of the ADBS suggests
that field samples of HI-selected sources do show a steep slope, while optically-
selected samples and cluster samples show a shallower slope. We conclude with
a discussion of these results and future prospects in §5.

2. Previous Arecibo Surveys and the Importance of Completeness

Determining the sensitivity limit of an HI survey is, in many ways, more critical
than the size of the survey. If the wrong limit is used, it will systematically
bias the mass function. The term “sensitivity limit” is itself a misnomer: the
completeness changes as a function of both signal strength and line width, and
it is not a sharp cut at some “$n$-$\sigma$” threshold, as is assumed in many studies.

For two earlier Arecibo HI surveys (Zwaan et al. 1997; Spitza & Schneider
1998) a $V/V_{\text{max}}$ test indicates that the samples are not complete to “5–$\sigma$” as
is traditionally assumed (SSR). In particular, the Zwaan et al. sample did not
satisfy the $V/V_{\text{max}}$ test unless a significantly higher cutoff level was assumed.
This higher effective noise level means that Zwaan et al. were sensitive to low
mass sources within a smaller volume than originally claimed, and therefore the
density of these sources is higher than they determined. By contrast, the volume
within which high mass sources were detectable is bandpass limited, so the net
effect of underestimating the limiting sensitivity is to suppress the steepness of
the mass function.

In addition, the incompleteness of the two surveys did not follow the usual
assumption that noise scales as the line width as $w^{0.5}$, as is expected from sim-
ple statistical arguments (e.g., Schneider 1996). Both Arecibo samples showed
a tendency to be less complete for wider-line profiles with an effective cutoff
$\propto w^{0.75}$. This width dependence implies a lower completeness for wide-lined
galaxies. A likely source of this problem is the baseline subtraction. Both au-
tomated methods and visual examination generally identify which channels to
mask from the baseline fit by their deviation from neighboring channels. When
the signal is spread over more channels, the difference from neighboring channels is reduced, and the channels may not be masked. Since wide-line signals are usually from HI-massive galaxies, this will suppress the counts at the high mass end, although the effect is usually minor since high-mass sources tend to be bandpass limited. Applying a \( w^{0.75} \) cutoff, both samples passed the \( V/V_{\text{max}} \) test and were consistent with each other.

For these earlier Arecibo samples, we assumed a sharp cutoff at the ratio of signal-to-noise (\( S/N \)) that passed the \( V/V_{\text{max}} \) test. To determine the completeness as a function of \( S/N \) in the ADBS, we generated a set of synthetic signals with random positions, line-widths, and line-strengths, and inserted them into the observing database. The sources had profile shapes that were modeled to look very similar to typical galaxy HI line profiles. We included sources ranging from several times weaker to several times stronger than a first-guess at our typical detection limit. These fake signals were added to the ADBS spectra before any of the “baselining” steps were performed. We were then able to test how efficiently our recovery process worked so that we could characterize the probable fraction of sources we were missing for any line width and \( S/N \) value.

In Fig. 1a, we show the fluxes and line widths of the synthetic sources, indicating the undetected sources by open circles. The plot is a little deceptive at the wide-line end of the plot in that there are many more detected sources (shown as gray dots) than are visible in the plot because the dots run together. The diagonal line in the figure has a slope \( \propto w^{0.75} \), which is a good description of the boundary below which very few sources are detected.

In Fig. 1b, we show the fraction of recovered synthetic sources as a function of \( S/N \), where we have folded together sources with different line widths by

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**Figure 1.** (a) A plot showing the fluxes and line widths of synthetic sources. Solid gray circles indicate sources that were recovered—note that these points run together, so that the large number of them is not obvious. The open circles indicate sources that were missed. The diagonal line shows a width\(^{0.75}\) dependence. (b) The completeness fraction as a function of the effective signal-to-noise ratio. The smooth curve shows an error function fit to the results for the synthetic sources.
dividing first by a value $w^{0.75}$. The value of $S/N$ is scaled so that it gives the normal value of $S/N$ for a source $300 \text{ km s}^{-1}$ wide (see SSR). The shape of the resulting completeness curve is quite similar to an error function. This is what one would expect for Gaussian noise added to an underlying signal—some sources are pushed below the threshold for detection while others are pushed above it.

Note that about 10% of high $S/N$ synthetic sources were not recovered. These sources generally fell on top of local Galactic HI emission, radio interference, or bandpass edges, making detection difficult. In the final calibration of the space density of these sources, this is an important adjustment, but it does not affect the slope of the mass function.

3. The $V_{tot}$ Method and Resulting Mass Functions

Using the completeness function derived above, we can accurately determine the effective search volume of our survey for each detected source. We do this by determining the distance to which a source could have been detected as a function of (1) beam offset, (2) rms noise at each observed position, and (3) frequency dependence of telescope gain. We then integrate over all of these possibilities, weighting the volume by the completeness function, to derive the total effective volume within which each source might have been detected, $V_{tot}$. (This is sometimes called $V_{max}$ but this is confusing because it is different than the value used in the $V/V_{max}$ test.) We have tested the $V_{tot}$ method quite extensively with simulations, and find that it does an excellent job of recovering the input mass function.

Weighting the volume elements by the completeness function solves the problem of dealing with sources near the completeness roll off. For example, for each source that is detected at the 50% completeness point, a second one is missed. Therefore the space density of these sources is twice as high as the detected source implies, or, effectively, half as much volume was searched at the distance where the source becomes this weak.

The resulting mass function of the ADBS field galaxies is shown in Fig. 2a. This function is based only on galaxies farther from the center of the Virgo Cluster than $27^\circ$ as we discuss in the next section. The field mass function displays a fairly good match to a simple Schechter function with a slope of $\alpha = -1.6$. A Schechter function with $\alpha = -1.2$ sits well below our curve. Note that the points are unequally spaced because they were grouped in intervals to maintain at least 6 sources per point, except the highest mass bin, which includes only 1 source. The error bars show the 95% confidence interval based on Poisson statistics for small numbers of sources (Gehrels 1986).

To match the shallower sloped Schechter function, the effective search volume would have to be $> 2 \times$ larger for sources with masses $< 10^9 M_\odot$, rising to $\sim 5 \times$ larger for sources with masses $< 10^8 M_\odot$. This would require that the survey sensitivity is $\sim 1.7 \times$ smaller than actually measured (once bandpass limits are properly accounted for). Such a large effective search volume is unsupported by our completeness measurements and would make our sample fail the $V/V_{max}$ test.
Figure 2. (a) The field HI mass function based on the ADBS. (b) Comparison of the ADBS field mass function with the measurements from two earlier Arecibo HI surveys (SSR). In both figures the error bars show 95% confidence intervals, and the two dotted curves show Schechter functions with slopes of $\alpha = -1.2$ and $-1.6$.

We also tested our completeness against sources from the Zwaan et al. (1997) $23^\circ$ strip, which one of our driftscans nearly overlapped. Their survey integrated about 20–30 times longer in the area covered, so that they provide a good check of our completeness, albeit within a relatively small area. We detected six of their sources with S/N as low as 5.1, and detected none of the 19 others with S/N as high as 3.1. Unfortunately, there are very few sources in the range where we might test the shape of the completeness roll off.

In Fig. 2b, we show the measurements from our analysis of the two earlier Arecibo blind surveys. These earlier data suggested a fairly shallow slope that begins rising below about $10^8M_\odot$ of HI. The ADBS mass function is in reasonable agreement at the high and low mass ends, but the middle range is significantly lower in the previous samples. We suspect this difference may reflect a dependence of the mass function associated with LSS, as we discuss next.

4. The Effects of Large Scale Structure

As we showed in our analysis of the earlier Arecibo samples (Schneider et al. 1998), corrections for density variations along the line of sight due to LSS are generally small. We based this on the density variations of optically-selected sources, which are thought to be more concentrated to high-density regions than HI-selected sources, so that these were probably over-corrections.

However, such density corrections assume that the shape of the mass function is independ of density. Otherwise, the density effects will be reflected in different ways depending on the survey sensitivity and the distances of any significant density structures along the line of sight.
Figure 3. (a) The density structure in the vicinity of the Arecibo blind surveys based on optical catalogs of galaxies. The solid and dot-dash lines show the results for the field and Virgo ADBS samples. The dotted and dashed lines are for the Zwaan et al. and Spitzak & Schneider samples respectively. (b) The field and Virgo HI mass functions. The Virgo function is shown as a dot-dash line, while three separate curves are shown for the field mass function based on differing assumptions: correcting for LSS or not, and showing the effect of applying a different low-velocity cutoff (see text). Model Schechter functions are shown as in Fig. 2a.

Based on the distribution of optically selected sources in the neighborhood of our surveys, and using corrections described in SSR, we derived the average density distribution for the ADBS shown in Fig. 3a. We found that outside of $27^\circ$ from Virgo, the average density at each redshift was relatively uniform, while within this radius there was a strong peak in density near the Virgo redshift. The figure also includes the density distributions for the two previous Arecibo surveys (SSR), which both show significant peaks at the Piscis-Perseus redshift.

The resulting mass function inside and outside the Virgo cluster is shown in Fig. 3b. Inside the Virgo region, the uncorrected mass function has a higher density than for the field sample, but the LSS corrections in this region drive the corrected density of sources below the field mass function. The Virgo mass function appears to be consistent with a shallow slope of the Schechter function.

By contrast, because of the relatively uniform density in the field sample region, the LSS correction has almost no effect on the final mass function. Two nearly indistinguishable curves show the field mass function with the LSS density correction turned on and off. We also show the effect of changing the minimum redshift cutoff from 100 to 300 km s$^{-1}$; the result is, again, almost indistinguishable.

Another concern is the effect of random velocity errors on the mass function. Because of the effects of local dynamical motions and large scale flows, our use of the Hubble law to derive galaxy distances generates an uncertainty in the distances and masses. Because of the larger volume at larger distances, one might fear that this effect would scatter more sources to smaller distances than...
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vice versa, and therefore bias the lowest-mass bins. However, if the Schechter slope is steeper than $\alpha = -1.0$ (which every analysis agrees with), the effect is reversed—the larger number of low mass sources overcomes the volume difference and the low-mass bins should be depressed. We have tested this with simulations, and confirm this conclusion.

We have also tested the effect of using alternative distances based on the POTENT model of local large scale flows (Bertschinger et al. 1990). This model shifted points slightly, but well within the error bars shown in the derived mass functions.

5. Discussion

The difference seen in and out of the Virgo Cluster region suggests a strong environmental dependence of the HI mass function. It is perhaps not surprising that low-mass HI sources are rare in a cluster where a deep gravitational potential is needed to retain a galaxy’s gas against the effects of ram-pressure stripping. This might explain why the mass function appears much more similar in shape to the luminosity function of optically-selected galaxies.

The shallow mass function seen in moderate-density groups and clusters may be explained by related effects. For example, even though Ursa Major has a long crossing time and no evidence of a hot intracluster medium, the fact that the mean density is an order of magnitude higher than the field implies that the region has been locally converging with respect to the Hubble flow. This in turn suggests that the rate of interactions and mergers between low-mass HI sources and nearby galaxies will be greatly enhanced, again suppressing the low-mass end of the mass function.

A density dependence of the HI mass function could be important for the earlier Arecibo surveys. They covered a small area of the sky, and are therefore subject to localized differences in the HI mass function. In particular, both derived a substantial fraction of their high-mass counts from the Pisces-Perseus supercluster region, while the low-mass sources were detected nearby in regions where the density of sources is more similar to the norm for field galaxies. This contrast in LSS density for different mass sources might explain the differences from the ADBS survey, which covered a much larger area of the sky more shallowly. As a result the ADBS survey volume (excluding the Virgo Cluster) is more representative of the field.

The effects of large scale structure do not explain all of the differences between surveys, however. We comment again on the importance of producing testable measures of the completeness of HI surveys. There are too many subtle effects in the data-processing stream to simply declare a limit based on what is expected or detected. As we have shown, some low $S/N$ sources are likely to creep into a sample and may suggest a better sensitivity than is warranted. There are also clearly peculiar effects on the completeness as a result of source linewidth that may differ depending on the precise analysis procedure.

An additional effect that we have not explored, but which may be especially important for higher-resolution synthesis mapping, is the effect of source size. For example, many of the low-mass sources detected in the ADBS appear to have much larger HI diameters than their optical sizes; some appear extended
even relative to the Arecibo beam. Spreading the emission over such a large area will suppress such sources’ detectability in synthesis mapping, but may enhance the chance of their detection in sparsely sampled surveys like the ADBS.

The competing effect of confusion mainly influences single-dish measurements of the mass function. Since the two-point correlation function indicates that galaxies tend to cluster around other galaxies, the challenge for a large-beam 21 cm instrument is to separate sources and determine which “should have been” detected based on the survey sensitivity.

It will do little good to conduct larger surveys if the potential biases caused by selection effects are not well understood. The good news is that with modern computational resources, it is relatively simple to model false sources and to insert them into raw survey data. Effects of source size and confusion can be established directly, and then a more useful comparison of results can be carried out.

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