Searching for the lowest mass galaxies
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Summary and future prospects

This chapter summarises the work that has been carried out and which is presented in this thesis. We will look retrospectively at the goals stated in Chapter 1 and compare them with the achievements. For the interested reader, a more detailed summary of the content of the individual chapters is presented in Subsections 6.1.1 to 6.1.4, where some of the results will be repeated. After the summary, we will discuss possible projects to carry out in the future. Most of the projects discussed are not a direct extension of the work presented in this thesis. They can be understood as suggestion for a future direction to interpret results obtained from the thesis project.

6.1 Summary of the main results

At the beginning of this thesis (Chapter 1) we identified three goals:

• to make an inventory of objects with HI masses in the range of about $10^6$ to $10^8 \, M_\odot$

The WSRT CVn survey has been used to carry out an inventory of all HI objects in the region of about 86 deg$^2$ covering the recession velocity range from approximately -450 km s$^{-1}$ to approximately 1330 km s$^{-1}$. The survey was successful in searching for the lowest mass galaxies: 37% of the detected objects has HI masses below $10^8 \, h_{70}^{-2} M_\odot$, and about 86% of all detected galaxies have profile widths measured at the 50% level of the maximum in the integrated spectra less than 130 km s$^{-1}$. We do not find any truly isolated, self-gravitating gas-clouds without starlight.

• to construct the H1MF

70 detections from the WSRT CVn survey have been used to construct the H1MF. A slope of the WSRT CVn survey H1MF is -1.17, significant down to
The slope of the H1MF is most sensitive to the binning (or to the low number statistic in the individual bins), and less sensitive to the uncertainties in the measured parameters. In all cases considered, the slope is shallower than the slope of -1.8 of the halo mass function, derived analytically (e.g. Press & Schechter 1974).

- to compare the properties of the lowest HI mass and/or narrowest profiles objects to the properties of objects with larger HI masses and/or broader profiles

Using three or five optical pass-bands and the HI properties of the galaxies, we conclude that galaxies with the smallest HI masses are at the same time the optically faintest systems and their optical diameters are smallest too. Galaxies with smallest HI masses generally have the HI mass-to-light and baryonic mass-to-light ratios higher than galaxies with larger HI masses. Their total gas fractions, $M_{\text{gas}}/ (M_{\text{gas}} + M_*)$, are distributed over the whole range of possible fractions (ranging from 0% to 100%), and their $g-r$ colours cover the whole range of colours covered by the galaxies with all HI masses. The Tully-Fisher (TF) and Baryonic TF (BTF) relations suggest that even galaxies with the narrowest profile widths follow the (B)TF relations established by faster rotating and brighter galaxies, though the scatter in the (B)TF relations is substantial. Our results do not support the idea of a relatively stronger removal of the baryonic gas in the low-mass galaxies, than in the more massive ones.

6.1.1 The WSRT CVn survey (Chapter 2)

A new extragalactic HI survey was carried out using the Westerbork Synthesis Radio Telescope (WSRT) in the direction of the Canes Venatici (CVn) groups of galaxies. The observations, 60 × 12h in mosaicking mode, were split in three runs during 2001, 2002 and 2004. The observations cover approximately 86 deg$^2$ in 1372 individual pointings. The final 1372 three dimensional (RA, Dec, V) datacubes produced by combining the data from the individual pointings have a typical spatial and velocity resolution of 30 × 60 arcsec$^2$ and 33 km s$^{-1}$, respectively, with a typical noise of 0.86 mJy Beam$^{-1}$ per velocity resolution element.

An automated search technique was developed to find the HI emission in the datacubes based on the counting of all pixels with positive and negative flux values. The search process yielded 70 detections. Of these, 69 can be identified with galaxies previously detected in the optical wavelengths. One HI detection is without an optical counterpart and is in the proximity of the larger galaxy NGC4288, separated by a few arcmin on the sky and $\sim 110$ km s$^{-1}$ in velocity. A new population of truly isolated self-gravitating HI clouds, without any starlight, has not been detected, in agreement with previous blind HI surveys.

We measured the various HI properties of the detected systems, such as the integrated flux, profile widths and the HI size. The distributions of these properties is in good agreement with corresponding distributions of the HI parameters obtained from the HI Parkes All Sky Survey (HIPASS, Meyer et al. 2004, the largest blind HI survey up to date), and extend these distributions to objects with about ten times lower integrated flux values. Our sample of detected objects is dominated with dwarf galaxies (or at least dwarf galaxy candidates): about 86% of all detected galaxies have profile widths measured at
6.1: Summary of the main results

the 50% level of the maximum in the integrated spectra of less than 130 km s\(^{-1}\).

6.1.2 The H\(_I\)MF in the volume probed by the WSRT CVn survey (Chapter 3)

It is straightforward to calculate the H\(_I\) mass of an objects when the integrated flux and the distance to the object is known. Using the three models of the velocity field and 64 detections with independently estimated distances in the larger area covered by the CVn constellation (limits given by Karachentsev et al. [2003b]), we conclude that recession velocities follow the Hubble flow fairly well (in the Local Group frame), with a dispersion of about 103 km s\(^{-1}\) for the detections at distances below 10 Mpc and a higher dispersion of about 290 km s\(^{-1}\) for objects detected at distances between 10 and 20 Mpc. We derive the distances to the objects assuming a Hubble flow with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\) or adopting the independently estimated distances from the literature, whenever possible. The H\(_I\) masses calculated span a range from 6.48 to 9.89 expressed in logarithmic units of \(h^2_{70}\) M\(_\odot\). A fraction of 37% of the detected objects has H\(_I\) masses below \(10^8\ h^2_{70}\) M\(_\odot\), making this the H\(_I\) selected sample with the highest fraction of H\(_I\) low-mass objects.

The H\(_I\) mass function (H\(_I\)MF) provides the space density of the H\(_I\) detections per given interval of H\(_I\) mass. This distribution is described well with a Schechter function, commonly used to approximate also optical and infrared luminosity functions. The best-fit Schechter function describing the distribution of the H\(_I\) objects detected in the volume probed by the WSRT CVn survey has parameters \(\alpha = -1.17\), \(\log(h^2_{70}M_{HI}^*/M_\odot) = 9.57\) and \(\phi^* = 0.125h^3_{70}\) Mpc\(^{-3}\) dex\(^{-1}\). Our result is valid down to \(\log(h^2_{70}M_{HI}^*/M_\odot)=6.40\), the lower limit of the lowest mass bin used to construct the H\(_I\)MF of the WSRT CVn survey. The resulting slope is at the lower end of the slopes established by recent H\(_I\) surveys - both blind surveys and surveys based on the optically selected galaxies.

The parameters of the fitted Schechter function are highly dependent on the binning. After selecting a suitable binning, the slope of the H\(_I\)MF may be steepen by -0.05 when using the HIPASS H\(_I\)MF value for the \(M^*\) parameter, flatten by 0.02 when introducing the realistic scatter in the distances and steepen by -0.04 (from the \(\chi^2\)-average) when adding the typical uncertainties in the integrated fluxes.

6.1.3 More “light” on the smallest H\(_I\) objects from the WSRT CVn survey (Chapter 4)

While the spirals and large irregular galaxies are dominated by differential rotation, this is not clear for the smallest irregular galaxies. To obtain detailed kinematic properties of some of the smallest detected galaxies in the WSRT CVn survey, we have undertaken the H\(_I\) follow observations with the WSRT telescope. In total, we obtained useful data for 23 galaxies detected in the WSRT CVn survey. The velocity resolution of the datacubes produced for the individual detections ranges from 4 to 12 km s\(^{-1}\) (compared to the velocity resolution of 33 km s\(^{-1}\) reached in the survey).

While the total integrated fluxes and peak fluxes (in the spatially integrated spectra) and systemic velocities do not show any systematic offset when compared to these parameters measured from the survey data, almost all profile widths obtained from the follow-up data are narrower than when measured from the survey data, with the difference being larger for the narrower profiles. We identify this offset as the deficiency of the
method of Bottinelli et al. (1990) to correct properly for the instrumental broadening of the profile widths. Another important conclusion regarding the data handling is that the traditionally used $2\sigma$ masks to identify the HI emission with the regions defined by the pixels with flux values above or equal to $2\sigma$ in the data smoothed to the lower spatial resolution will significantly overestimate the total integrated flux of the faint HI emitters (below 10 Jy km s$^{-1}$).

By inspecting the position velocity diagrams, velocity fields and global profiles of the detections, we conclude that the majority of them, 20 out of 23, show a sign of rotation. From the rotating 20 detections, 7 did not show a sign of rotation in the survey data. Our result is in accordance with the recent finding by Begum et al. (2006, and references therein) that the high velocity resolution and sufficient sensitivity may reveal the presence of rotation patterns, not seen in the data observed with the lower velocity resolution.

6.1.4 Optical and HI properties of the complete WSRT CVn sample of HI detected galaxies (Chapter 5)

Surface photometry in $g$, $r$ and $i$ (from the Sloan Digital Sky Survey, SDSS, York et al. 2000) for 69 galaxies from the WSRT CVn survey which have an obvious optical counterpart, and in $B$ and $R$ for 29 galaxies was obtained and compared to the HI properties of the WSRT CVn galaxies.

This comparison revealed various trends. Galaxies with smaller HI masses are fainter in the optical than galaxies with larger HI masses. Fainter galaxies have higher HI mass-to-light and baryonic mass-to-light ratios than brighter galaxies. The median $M_{\text{HI}}/L_\lambda$ value of the WSRT CVn galaxies is 0.91 in the $B$-band (including also HYPERLEDA data for 29 galaxies) and 0.89 in the $r$-band. The gas-richness in the $B$-band is about two times higher than the sample of optically selected late-type galaxies by Roberts & Haynes (1994). The bluer galaxies have higher gas fractions (defined as $M_{\text{gas}}/M_{\text{bar}}$) than redder galaxies. The gas fractions of faint galaxies span a range of all possible fractions, while for brighter galaxies there may be an upper limit in the possible gas fraction. The various relations suggest that faint (dwarf) galaxies are less efficient at turning gas into stars.

The TF relation has been investigated using various subsamples of the WSRT CVn galaxy sample. The main conclusion is that the TF relation established by the WSRT CVn galaxies follows the TF relation established by brighter and faster rotating galaxies. Here, fainter and slower rotating WSRT CVn galaxies do not indicate any break in these TF relations (a tendency that faint galaxies, $M_B < -14$ mag, lie below the TF relations of the literature $B$-band TF relations is seen). The scatter is higher than the scatter of the TF relations derived from the samples which include only brighter and faster rotating galaxies. The scatter can not be reduced by excluding detections with the largest measurement errors. A small reduction is seen when constructing the TF relation for the sample of galaxies for which an indication exists that the rotation curves reached the flat part. The scatter is also large when constructing the Baryonic TF (BTF) relation. When compared to previous estimates of the BTF relation in the literature, our data provide no indication that galaxies with small profile widths (e.g. below 90 km s$^{-1}$) lie systematically below the BTF established by larger systems. This result is not in agreement with the models proposing the removal of baryons from galaxies with $V_{\text{max}} < 100$ km s$^{-1}$ (e.g. Dekel & Silk 1986, Dekel & Woo 2003). Removal of baryons in
these galaxies would result in a break in the slope of the BTF relation. We obtained the slope of the BTF relation of $\sim 3$, practically equal to the slope predicted from the virial theorem, suggesting that baryonic mass removal mechanisms are not more efficient in dwarf galaxies than they are in more massive and luminous galaxies.

6.2 Suggestions for future work

In this thesis we presented number of results based on the observational data. To interpret these results in the framework of the standard theoretical paradigm, an additional link is needed. Here, we present few suggestions for future work, which could lead to a more direct comparison between the (HI) observations and the predictions of the standard cosmological model.

6.2.1 History of low-mass galaxies: hierarchical versus anti-hierarchical

The data obtained from HST and VLT/FLAMES have provided significant advances towards understanding the smallest systems. These data allow to constrain the colour-magnitude diagrams of resolved stellar populations and derive their star formation histories into great detail. These studies revealed surprising evidence of the complex and very diverse evolution history of the dwarf galaxies, clearly different from the single-age, single-metallicity history which is characteristic for globular clusters. Even galaxies within the same morphological subclass differ in their properties, especially their enrichment histories and/or time and duration of their star formation (Grebel 2001b). The only common property to all Local Group dwarf galaxies studied in sufficient detail so far is the presence of an old population (Grebel 2001a).

Use of resolved stellar population is the most accurate and reliable method to derive a galaxy’s star formation history, but is restricted only to galaxies in the Local Group and Local Volume ($< 5$ Mpc). For more distant galaxies studies of star formation histories rely on integrated photometry and spectroscopy in combination with stellar population models.

It has been already established that relatively blue $B$ - H$\alpha$ colours of many gas-rich LSB galaxies (e.g. Bothun & Caldwell 1984; de Blok et al. 1995) do not agree with an exponentially declining or constant star formation history (over the last few billion years). A recent analysis of a sample of the HI detected galaxies from HIPASS, combining their HI and $B$, $R$ and H$\alpha$ properties, indicates that this sample of galaxies has a current star formation rate which is fairly high when compared to that in the past. The colours, equivalent widths, and star formation rates per unit HI mass of these HI selected galaxies indicate the presence of stellar populations with young mean ages (Helmboldt et al. 2005). It seems likely that episodic star formation events define the recent star formation history of the typical LSB disk (Helmboldt et al. 2004). Even the smallest detected galaxies, with HI and stellar masses of about $\sim 10^7 M_\odot$ are blue LSB galaxies and undergo a burst of star formation (Kovač et al. in preparation).

The size of recent redshift surveys of galaxies, such as the Two-Degree Field Galaxy Redshift Survey (2dFGRS, Colless et al. 2001) and the SDSS, provides a means to study statistical properties of galaxies. Using the SDSS spectra Kauffmann et al. (2003) show...
that, at stellar masses around $3 \times 10^{10} M_\odot$ galaxies separate into two distinct classes of spectral and structural properties. The transition around this stellar mass can be seen in the colour-magnitude diagram (Baldry et al. 2004), and it appears that there is also a transition in gas-richness of galaxies (Kannappan 2004). This also corresponds to the transition in galaxies with “young” and “old” populations. Faint low-mass galaxies with low concentrations and surface mass densities have young stellar populations, ongoing star formation and blue colours (Kauffmann et al. 2004). Using the SDSS data to reconstruct the transformation of baryons into stars over time, Heavens et al. (2004) find that “the bigger the stellar mass of the galaxy, the earlier the stars were formed”. These results suggest a very different formation history for low- and high-mass galaxies: while dark matter assembly is hierarchical - small objects form first, stellar assembly history is anti-hierarchical - large objects form their stars first (Jimenez et al. 2005).

From the above it follows that low-mass galaxies are not simple systems evolving passively after their first burst of star formation in the dawn of the Universe. It is clear, that more detailed studies of their star assembly histories are needed to establish their proper place in the (star) formation models.

It is well known that the environment plays an important role in the process of star formation. While earlier works are based on comparison of results obtained from galaxy clusters, groups etc. large redshift surveys provide samples of galaxies selected without respects to the environment. The additional analysis of spectra of SDSS galaxies in Kauffmann et al. (2004) demonstrate that the star formation history is the property of galaxies which is most sensitive to the environment (not more than 1 Mpc from galaxy). This dependence is strongest for galaxies with stellar masses less than $3 \times 10^{10} M_\odot$.

The star formation histories of galaxies selected at the faint end of the luminosity and H\text{I} mass function in different environments can be studied in the nearby Universe with the already available multi-wavelength observations.

The galaxies suitable for this kind of study can be selected from the SDSS, especially from the “low-redshift catalogue” (Blanton et al. 2005) which contains information on $\sim 30000$ galaxies detected in SDSS, second data release (Abazajian et al. 2004). These galaxies are at distances in the range between 10 and 150 $h^{-1}$ Mpc and they are of extremely low luminosities (up to $\sim -12.5$) and detected in a wide range of environments. The catalogue is already cross-correlated with numbers of additional surveys, such that a number of galaxies already have measured photometric properties in $ugrizJHK_s$ bands. For some galaxies H\text{I} data might be obtained additionally. The star formation histories of low-mass galaxies can be constrained by comparing the observed SED of the galaxy (from continuum spectrum combined with the UV to near-IR imaging photometry) to the modelled SED; the latter can be done using the existing population synthesis codes (Vazdekis 2001; Bruzual & Charlot 2003) and a parametrisation of the assumed star formation history. The optical, infrared and possible UV data of the selected low-mass galaxies will provide information on how much mass of the galaxies is in the form of stars formed during the past and present epochs of star formation. The H\text{I} data will provide information on how much of the fuel is still left for this process. By carefully constructing the star formation histories of galaxies through modelling of various physical processes, the amount of H\text{I} during the history of a galaxy will be established.

By studying the data over a large wavelength range, different episodes in evolution of low-mass galaxies will be addressed; that will shed more light on different roles and types of feedback and cooling. Combining the constrained star formation histories of low-
mass galaxies with the halo properties in which galaxies reside in different environments will place constraints on galaxy formation process of the smallest systems. Ultimately, one will be able to confront star and galaxy formation histories of low-mass galaxies to establish if they are hierarchical or anti-hierarchical.

6.2.2 Haloes in a function of the environment?

To understand the role of the environment on the observed galaxy properties it is critical to understand how the physical parameters change in what is defined as different environment. Kauffmann et al. (2004) used the GIF simulations (http://www.mpa-garching.mpg.de/galform/virgo/hrs/) to establish the connection between the local galaxy density and dark matter haloes. They conclude that galaxies in higher densities occupy more massive haloes. Due to the resolution limit of GIF simulations these studies are only possible for galaxies with stellar masses above \(10^{10}\ M_\odot\). It was assumed a priori that the galaxy population in a halo of a given mass depends on the halo mass alone, while the dependence on the environment is only a reflectance of the different halo mass. This assumption is based on some theoretical work (e.g. Mo & White 1996) and numerical simulations (e.g. Percival et al. 2003). It is surprising therefore that recent huge Millennium simulations revealed different properties of galaxies in haloes of the same mass in different environments (Gao et al. 2005). In the same work low mass haloes which were formed earlier show stronger clustering compared to the haloes of the same mass formed recently. This result contradicts the often used assumption that the galaxy content of a halo of given mass is statistically independent of its larger scale environment. To place the observed trends in the framework of CDM models the proper link between the measurable parameters and dark matter and environment is needed.

To characterise environment one can assign galaxies to a halo of a certain mass (circular velocity). This has been done for galaxies in dense environments, where there is a sufficient number of galaxies in a virialised structure to calculate the halo mass using the velocity dispersion of halo members. To include haloes which host only one galaxy into this kind of analysis and use them to constrain formation models, their H\(_I\) properties can be used. Here the detected hydrogen in galaxies is the best tracer of the potential well formed by the dark matter halo. Measuring the velocities of galaxies from the H\(_I\) data (in the best case the velocity at which the rotational curve flattens) in different environments will give the answer on the dependence of the velocity width on the environment. Using the relation between velocity widths from the H\(_I\) observations and the circular velocity of the dark matter haloes will give answers on the dependence of halo mass (calculated from the circular velocity) and the environment, the important cosmological question addressed recently. The H\(_I\) data of galaxies selected in the optically different dense environments may be used also to study correlations between H\(_I\) and other galaxy’s properties as a function of environment.

6.2.3 Linking the observed properties of galaxies to host haloes

In the current cosmological paradigm, it is well established that galaxies reside in dark matter haloes. However, the way on which galaxies populate their hosts is still a matter of debate. In Yang et al. (2003) three different methods to link galaxies to their dark matter haloes have been distinguished. One of the methods is based on assigning halo properties
based on the observed galaxy’s properties (as the proposed project discussed above). The second method consists of building a galaxy formation model using numerical simulations and/or semi-analytical modelling, while the third method is based on large surveys, and a link between a galaxy and the host halo is established only in a statistical manner.

The last approach uses the so called halo occupation function (e.g. Jing et al. 1998; Bullock et al. 2002). This function contains only information about the number of galaxies per halo above a certain mass. The step further is obtained with the “conditional luminosity function” which gives the average number of galaxies in a luminosity bin as a function of halo mass. This approach has been further explored in dividing galaxies on central and satellite (e.g. Vale & Ostriker 2004) or early- and late-type (e.g. van den Bosch et al. 2003).

I propose to take a similar approach and build the “conditional H I mass function”. Due to the small numbers of galaxies observed in H I surveys, this can not be done directly. One approach is to use scaling relations between the amount of H I detected in the galaxy and other measured properties of the galaxy. In this case one has to be careful how to deal with the scatter, which is typically large in relations connecting H I to other properties (e.g. Kannappan 2004). Another way is to develop probability distributions of the amount of H I in a galaxy as a function of the properties of the galaxy such as its size, luminosity, colour etc. Using the existing probability function to link the luminous content of galaxies to their hosting haloes, the multi-parameter probability function of H I amount in the dark matter haloes will be developed.

This methodology can be explored further to link the various properties of galaxies (such as their star formation rate, velocity width, size etc. in possible combination with luminosity, colour and/or H I amount) to their hosting haloes. Of great importance for this project will be the results from the discussed project Haloes in a function of the environment? If the project reveals the halo dependence on the environment all models of “the halo occupation function” and “the conditional luminosity function” has to be corrected for this effect.