A Westerbork blind HI imaging survey of the Perseus-Pisces filament in the Zone of Avoidance

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5 Summary and Future Work

Abstract

The main results from the study that has been carried out in this thesis are summarised in this chapter. In the first part a brief statement on the motivation behind this work and outline of the main goals is provided and the main results summarised. The second part contains a discussion on the future prospects and planned studies to be carried out that are directly related to the work conducted in this thesis.

5.1 Introduction

This project was started with the main goal of mapping a major overdensity of the Perseus-Pisces Supercluster (PPS) that had remained largely unexplored to date. The interest in this overdensity was motivated by hints of the potentially rich X-ray emitting 3C 129 cluster embedded therein, which also hosts two strong radio sources (Spinrad 1975). Due to its low Galactic latitude the galaxy composition of this cluster had not been investigated in detail despite it being a component of the expansive PPS filament. The high extinction levels in this region of the sky make finding galaxies at optical wavelength ineffective. The only way to investigate the galaxy distribution in this overdensity is through 21 cm line emission H I observations. The required H I-survey was conducted with the Westerbork Synthesis Radio Telescope (WSRT). With these radio observations we aimed to,

- construct a spectral data cube from which the H I properties of the galaxies in and around the 3C 129 cluster and its immediate surrounding regions in the PPS could be extracted,
- map the distribution of the galaxies on the sky and in redshift, and investigate how the large-scale structure of the PPS filament connects across the Zone of Avoidance,
- analyse the galaxy population of the 3C 129 cluster and study its properties in detail,
- characterise the cosmic environments within the surveyed volume and investigate the link between the galaxy properties and their environments.

In addition to these scientific goals, the project was also designed in such a way that it could be used as a pilot study for the upcoming H I-surveys to be conducted with Apertif. For this purpose, it provides data with which calibration, visualisation, source finding and characterisation techniques can be tested on real H I data cubes. It is absolutely vital to have a good handle on these issues before the large datasets from these forthcoming surveys start streaming in.

5.1.1 The WSRT H I-imaging of the Perseus-Pisces Supercluster in the Zone of Avoidance

A blind H I-imaging survey was performed targeting a wall-like structure that encompasses a potentially rich cluster. This cluster, known mostly from its X-ray emission as the 3C 129 cluster, is part of the Perseus-Pisces Supercluster filament that crosses the Zone of Avoidance (ZoA) around $(\ell, b, v) \approx (160.5^\circ, 0.27^\circ, 6000 \text{ km s}^{-1})$. Observations were carried out using the WSRT, comprising 35 individual pointings each observed for 12 hours. The pointings were arranged in a hexagonal mosaic similar to a single Apertif pointing. It covered an area of about 9.6 sq.deg centred at $(\ell, b) \approx (160.8^\circ, 0.9^\circ)$ and a radial velocity range of approximately $cz \sim 2000 - 16000$ km s^{-1}. The resulting spectral line data cube has an angular resolution of $23'' \times 16''$ and a velocity resolution of 16.5 km s^{-1} with typical noise levels ~ 0.4 mJy/beam. The survey configuration allowed for an H I-mass detection limit of $M_{HI} = 3\times10^8 M_\odot$ at the 6σ noise level assuming a line-width (w_{50}) of 150 km s^{-1} at the median distance of the PPS ($cz \approx 6000$ km s^{-1}).

Semi-automated methods based on Gipsy software tasks were used to search for the H I-emission from galaxies. The search resulted in 211 H I detections in the entire survey volume. Various H I properties of these galaxies were produced including integrated fluxes, line-widths, H I-column density maps and velocity field maps. The average measured line-widths (w_{50}) and H I-masses (M_{HI}) are about 132 km s^{-1} and $\log(M_{HI}/M_{\odot}) = 9.1$. Only 62% of the H I detected galaxies in our survey volume were found to have a stellar counterpart at near-infrared wavelengths as identified in the deep and high resolution UKIDSS Galactic Plane Survey (GPS) images, which is a testament to the challenges presented by extinction in the ZoA.

5.1.2 Linking large-scale structures across the ZoA

A total of four distinct overdensities were identified in redshift space in the survey volume. Of these, the two minor overdensities were located at the radial velocities of $cz \sim 2000-4000$ km s^{-1} (Aur 1; 15 H I-detections) and $cz \sim 12000 - 16000$ km s^{-1} (Aur 4; 37 H I-detections). The other two were major overdensities located at the velocity of the PPS of $cz \sim 4000-8000$ km s^{-1} (Aur 2; 87 H I-detections) and in the background of the PPS within the velocity range of $cz \sim 8000-12000$ km s^{-1} (Aur 3; 72 H I-detections). H I-detected galaxies located in these two major overdensities have H I-masses and line-widths in the range of $\log(M_{HI}/M_{\odot}) = 7.8-10.3$ and $w_{50} = 25-526$ km s^{-1} for Aur 2, and $\log(M_{HI}/M_{\odot}) = 8.6-10.3$ and $w_{50} = 28-322$km s^{-1} for Aur 3. Galaxies in the radial velocity range of the PPS were used to demonstrate that the Persues-Pisces Supercluster does indeed connect across the ZoA, thus confirming earlier indications (e.g., Focardi, Marano & Vettolani 1984, Chamaraux et al. 1990) of a PPS filamentary connection between the Perseus, the Pisces and the A569 clusters across the ZoA in this region of the sky. In fact, the large-scale structure maps by Jarrett (2004) have shown that the PPS may even connect all the way up to the A634 cluster which would make the PSS one of the largest filamentary chains ($>$ 100 Mpc) in the nearby Universe. Galaxies in the background of the PPS were shown to be part of a structure only known as CID15 in the reconstructed density and velocity maps from the 2MRS (Erdoğdu et al. 2006) and thus validates the accuracy of these reconstructed maps above and below the ZoA in this region on the sky.

5.1.3 The galaxy composition of the 3C 129 cluster.

Given that the only properties that were known about the 3C 129 cluster were based on its X-ray emission and its two embedded radio galaxies, a more detailed exploration requires information on its galaxy population. For this purpose a census of the galaxies within this cluster was conducted. This was carried out by combining the H I-detected galaxies with the galaxies identified in the near-infrared (NIR) taking advantage of the high resolution ($0.2''$/pix, seeing $\approx 0.8''$) images from the UKIDSS Galactic Plane Survey (UKIDSS-GPS). Photometry in the NIR J, H and K bands was obtained for about ~ 9700 galaxies within the WSRT H I surveyed area. Cluster members were selected by fitting the red sequence in the $(J-K)$ vs K colour-magnitude diagram. The resulting fitted slope of the 3C 129 cluster was found to be $\alpha = -0.023 \pm 0.002$ mag, similar to the Coma cluster ($\alpha = -0.017 \pm 0.009$), which lies at a similar recession velocity of $cz \sim 6000$ km s^{-1}. The cluster's spatial extent was defined to be within a radius of ~ 1.7 Mpc ($1.34 R_{200}$) motivated by where the galaxies became sparsely distributed. Within this radius 261 galaxies were identified in the UKIDSS-GPS images and visually confirmed. This process demonstrated the efficiency of fitting the red-sequence to identify cluster galaxies in the absence of redshift data. The high resolution of the UKIDSS-GPS images made it possible to estimate the morphologies of these galaxies. More than half of the galaxies seen in projection against the cluster region were found to be early-type galaxies (E and E/S0) and bulge-dominated spirals.

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The velocity and spatial distributions of the gas-rich, H I-detected galaxies and the gas-poor red-sequence galaxies are different in this cluster. Specifically, the early-type population that comprises the E and E/S0 galaxies dominates the inner regions of the cluster while the population of gas-rich galaxies that constitutes for 83% of late-type spirals, is found in the cluster outskirts. An obvious radial morphological segregation is seen within a radius of ~ 0.9 Mpc from the centre of the cluster where an increase of the early-type galaxies is balanced by a decrease of the late-type galaxies. Moreover, the H I-detected galaxies seem to strongly avoid the inner region within a radius of ~ 0.5 Mpc, thus pointing to a strong effect of the cluster's environment on the gas content of galaxies.

The richness of the cluster was examined by comparing its K-band luminosity function to those of two well-known clusters at similar redshifts. One being a massive cluster in the Great Attractor region, namely the Norma cluster ($M_K^* = -25.4 \pm 0.8, \alpha = -1.26 \pm 0.10, \phi^* = 27.8 \pm 2.4$

h^2_{70} Mpc^{-2}), also located in the ZoA but in the South, and the other being the Coma cluster ($M^*_K = -24.0, \alpha = -0.98, \phi^* = 76.0 \pm 3.0$ h^2_{70} Mpc^{-2}). The comparison showed that the 3C 129 cluster is quite rich as was suspected. The galaxy density in the core of the 3C 129 cluster is similar to that in the Norma cluster and slightly less than in the Coma cluster. This finding is consistent with the relative X-ray luminosities of these three clusters.

Additionally, the spatial distribution of galaxies in the core of the cluster showed a slight asymmetry aligned with the irregular distribution of the X-ray emission. This is consistent with the results from the X-ray analysis by Leahy & Yin (2000) who surmised that the 3C 129 cluster seems to have undergone a merger and has not reached a dynamically relaxed state yet. Furthermore, a large substructure dominated by gas-rich galaxies was found North of the main cluster at a slightly higher recession velocity. These observations seem to point to a scenario where the 3C 129 cluster might still be growing through the accretion of galaxies falling in along the PPS filament.

Overall, the examination of this cluster points to a diverse and dynamic environment that is relatively nearby from which studies of the environmental effects on galaxy properties would benefit.

5.1.4 Effects of the environment on H I-properties

The wealth of H I data from the WSRT PPZoA survey revealed a myriad of cosmic environments ranging from major galaxy overdensities, an X-ray emitting galaxy cluster to voids. This offered a unique laboratory in which H I-properties of the galaxies in these various environments could be examined under the same observational conditions.

The main environments of interest in the volume were the two major galaxy overdensities, one containing the 3C 129 cluster at the recession velocities of the PPS of $cz \sim 4000 - 8000$ km s^{-1} (Aur 2), and the other in the background of the PPS at $cz \sim 8000 - 12000$ km s^{-1} (Aur 3). Substructures in these galaxy systems were identified by performing the Dressler-Shectman test for the gas-rich H I-detected galaxies and by assessing the 2-dimensional galaxy distribution of the gas-poor galaxies using the adaptive kernel smoothing based technique applied in smoothed particle hydrodynamics. Both overdensities exhibit substructure and are unique in their galaxy composition and thus represent different environments. Galaxies in substructures located in the Aur 2 system were mostly found to be early-type galaxies while in Aur 3, substructures mostly contained late-type galaxies.

The H I-morphologies of galaxies in these substructures were examined by assessing asymmetries in their global H I profiles, integrated H I maps and kinematics. The well-known H I-morphology density relation is found, such that more disturbed H I morphologies are frequent in the larger and more densely populated galaxy groups, while in the less populated groups the H I is distributed more in regular disks. The result is thought to be due to the higher incidence of tidal interactions in denser environments.

An investigation of the H I-content of galaxies within the 3C 129 cluster revealed an H I-gas deficiency in the core of the cluster as indicated by the lack of H I-detections in this region. The cause of this gas-deficiency was examined by modelling the impact of the intra-cluster medium on the galaxies in the cluster. The ram-pressure stripping mechanism was found to be the dominant gas removal process in the core of the cluster. However, galaxies with significantly low H I-content were also found in the cluster outskirts. Most of these galaxies are located within galaxy groups inside the cluster radius and are falling into the cluster for the first time. Additionally, a similarly low H I-content was measured in the Aur 3 galaxy system in which no X-ray emission or galaxy cluster is known, thus confirming the importance of gas-removal processes occurring in galaxy-groups/filaments in the transformation of galaxies.

5.2 Future work

5.2.1 Perseus-Pisces Supercluster ZoA flow-fields

The H I observations conducted in the hidden region of the Perseus-Pisces filament have revealed overdensities that could contribute to ongoing studies aimed at fully understanding the dynamics of the Local Universe. The next natural step is to construct cosmic flow-fields in this region of the ZoA. This requires a decomposition of the detected galaxy velocities into their two components; the recession velocity which is caused by the expansion of the Universe and the peculiar velocity which arises due to the gravitational force caused by the non-uniform mass density distribution. Disentangling the two requires a distance indicator such as the Tully-Fisher (TF; Tully & Fisher 1977) relation, which is a correlation between the rotational velocities and absolute magnitudes. The rotational velocities of the galaxies will be acquired from the H I global profiles of the detected galaxies, and the apparent magnitude from the NIR photometry. With these parameters, the peculiar velocities using the

TF relation can be derived. This is possible using a new re-calibration of the TF relation for isophotal magnitudes (Said, Kraan-Korteweg & Jarrett 2015). This re-calibrated TF was customised especially for the ZoA where the derived total magnitudes are unreliable. The measured peculiar velocity field maps will provide information on the relevance of this overdensity and its immediate surrounding PPS.

5.2.2 Spectroscopic follow-up

For the work presented in this thesis the gas-poor galaxies that belong to the 3C 129 cluster were selected mainly based on their red-sequence using the NIR colour-magnitude relation. This method is effective at finding cluster galaxy candidates in the absence of optical spectroscopy since it has been shown to have a low contamination rate of about 5% at both near-infrared and optical wavelengths (Gladders & Yee 2000). Moreover, the slope of the red-sequence is similar for clusters at the same redshift while evolving with redshift (Gladders et al. 1998, López-Cruz, Barkhouse & Yee 2004). This is advantageous since the slope of the red-sequence can provide an estimate for the cluster redshift. However, the uncertainty on the redshift estimate has been found to be around 10% (Gilbank et al. 2007) as a result, structures that are close to each other in distance may be inseparable along the line-of-sight. It is therefore possible that some galaxies from the background overdensity at $cz \sim 10000$ km s^{-1} (Aur 3) could have entered the 3C 129 cluster sample. For this reason it is important to confirm the validity of this colour selection and verify that the selected galaxies are indeed cluster members and not interlopers from the background. This can only be achieved through optical or near-infrared spectroscopic follow-up, preferably with a multi-object spectrograph, such as the new WEAVE instrument on the William Herschel Telescope (Dalton et al. 2012), capable of taking spectra of up to 1000 targets at the same time. Although optical wavelengths might suffer from extinction, the catalogues compiled in this study contain the necessary positional and photometric information for all objects on the red-sequence within the H I survey area. This will make it easier to select only those sources that are likely to provide reliable measurements. Extending the number of redshift measurements will not only be valuable in confirming the members of the 3C 129 cluster spectroscopically, but it will also allow for detailed studies of the overdensity in the background. Examining the state of this structure will be useful in determining flow-fields in this region and compare these to those predicted from the 2MRS reconstructed maps by Erdoğdu et al. (2006).

5.2.3 The Cluster Dynamics

Obtaining additional spectroscopic redshifts for the 3C 129 cluster will improve membership designation of galaxies to this cluster. This is vital in determining the gravitational potential of the cluster, which generally is obtained from the dispersion of the line-of-sight velocities. Additionally, better redshift statistics will help avoid biases in the velocity dispersion and cluster mass measurements (Beers, Flynn & Gebhardt 1990, Ruel et al. 2014).

The velocity dispersion of the 3C 129 cluster is currently only estimated from the galaxies detected in H I or from the X-ray data. However, there are issues with both these measurements. First, the cluster velocity dispersion based on the H I detections is highly uncertain given that almost all of the H I detected galaxies lie outside the core of the cluster, which means that the velocity dispersion measured this way does not properly represent the densest regions of the cluster. Secondly, the X-ray analyses are hampered by the lack of redshifts, which means that the velocity dispersion had to be determined from the β-model of the 3C 129 cluster surface brightness profile (Leahy & Yin 2000). However, it is well-known that the β values derived from the X-ray surface brightness profiles are less than those computed from the actual galaxy velocity dispersions (Forman, Jones & Tucker 1984). As a result, not only is the dispersion uncertain but it would have likely translated into large relative uncertainties that dominate the derived density and temperature profiles of the 3C 129 cluster (Leahy & Yin 2000). Obtaining better redshift statistics will allow for more accurate measurements of these important X-ray parameters of the cluster.

With a larger redshift sample a more robust dynamical analysis can be conducted and the dynamical mass of the cluster computed. This is important in determining the cluster's role in, and the mass contribution to the PPS.

5.2.4 Radio Continuum and Star-Formation

The sensitivity of the data in the observed WSRT volume is excellent for examining the radio continuum emission of galaxies. This is useful for studying star formation rates of galaxies in the 3C 129 cluster environment. These galaxies produce radio synchroton emission through relativistic electrons in supernova remnants. The radio and far-infrared correlation shows a connection between the rate of supernovae and the dust heating produced by massive stars in these galaxies (Condon, Anderson & Helou 1991, Murphy et al. 2008). The radio continuum data will also provide a complementary diagnostic tool for studying the interactions of the late-type galaxies with the cluster environment. Recent studies have shown that gas stripping of the galaxies have local effects on the radio continuum in the core of clusters where ram-pressure is strong (Murphy et al. 2009, Vollmer et al. 2013). With the acquired WSRT data, investigations of this phenomenon are possible. Furthermore, the ram-pressure effect on star-formation rates can be studied in combination with data from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Churchwell et al. 2009) from the Spitzer program. Moreover, radio continuum data will provide an optimal data sample for studies of AGN in galaxy clusters, particularly in the infalling regions. This will give insights in AGN feedback on the surrounding gas at the galaxy-group scale where a mix of X-ray emission, H I and radio continuum has been shown to exist.