The ursa major cluster of galaxies
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Chapter 7

Highlights, Conclusions and Prospects

1 Unique sample

- A complete, volume limited sample of 62 equidistant spiral galaxies has been selected. This sample provides an unbiased inventory of the nearby field and forms a solid basis for the study of the TF-relations and of dark matter in spiral galaxies.

The Ursa Major Cluster of galaxies contains an excellent collection of late type spiral systems suitable to study the scatter in the Tully-Fisher (TF) relation and the structural properties of the dark matter haloes. It differs in nearly all respects from the classical clusters like Virgo and Coma. The 79 identified members of the Ursa Major Cluster, located at the same distance as the Virgo Cluster, display a very low velocity dispersion of \( \approx 150 \text{ km/s} \) and show no concentration toward any core. The sample is overwhelmingly dominated by late type systems and is representative for the galaxy population in the field. Since the crossing time is comparable to the Hubble time, only a few systems have been affected by tidal interactions. In fact, the principal reason to call this a cluster is the large number-density of galaxies in this region of the Local Supercluster, although the ensemble probably does have negative energy. Essentially all objects intrinsically brighter than the SMC are identified and make up a complete volume limited sample of 62 galaxies.

Another important advantage of this sample is the availability of optical and near-infrared surface photometry for all galaxies in the complete sample. In fact, all galaxies are photometrically imaged in the \( B, R \) and \( I \) passbands. Furthermore, 21-cm line synthesis observations have been obtained for all cluster members with detectable amounts of neutral hydrogen gas. From these HI data, rotation curves have been derived. Such detailed photometric and kinematic information on individual galaxies of a complete, volume limited sample forms a solid basis for investigations of the statistical properties of the TF-relations and the structural parameters of dark matter haloes. For both studies it is of crucial importance that all galaxies in the sample are at the same distance so that the relative luminosities, sizes and masses are accurately known.

2 Surface brightness bimodality

- In the near-infrared, stellar disks tend to avoid a certain regime of face-on central surface brightness around \( \mu_{\text{0}} \approx 18.5 \text{ mag/arcsec}^2 \). This gap in the surface brightness distribution is clearer when only the isolated systems are considered.

The critical new aspect of this dataset is the \( K' \) surface photometry of a complete volume limited sample. Even galaxies with the lowest optical surface brightnesses in our complete sample have been imaged in the \( K' \)-band and this has showed an unexpected new result. The distribution of \( K' \) face-on disk central surface brightnesses turned out to be bimodal. There seems to be a regime of central surface brightnesses around \( \mu_{\text{0}}(K') \approx 18.5 \text{ mag/arcsec}^2 \) which is avoided by galactic stellar disks. This bimodality becomes even more pronounced when galaxies with significant near neighbors are excluded from the analysis. This has lead us to identify two distinct families of galaxies in our sample, the High Surface Brightness (HSB) galaxies and the Low Surface Brightness (LSB) systems. It is speculated in Chapter 3 and tentatively confirmed in Chapter 6 that the bimodality in surface brightness has a kinematic signature as well. We make
the hypothesis that the disks of HSB galaxies are self-gravitating and those of LSB galaxies are not. We speculate that the gap in surface brightness is then related to a stability threshold at the epoch when most of the baryons were still in a dissipational gaseous form. Apparently, massive gas disks become unstable when they are on the verge of becoming self-gravitating. Gas disks with a high initial angular momentum can be pushed to this limit by loss of their angular momentum due to a traumatic birth or tidal interactions with near neighbors. Detailed high resolution hydrodynamic simulations of a collapsing gas disk are required to verify or falsify this hypothesis.

As an aside, it is worthy to note that present-day disks appear to have an upper limit to their gas surface density. Most gas disks with surface densities above $5-10 \, M_{\odot} \, pc^{-2}$ seem to be involved in interactions, are kinematically perturbed, or show active star formation.

3 An unbiased HI view

- An HI synthesis survey of the complete Ursa Major sample provides, for the first time, an unbiased HI view of spirals in the field and improves the statistics on the occurrence of warps (30%), lopsidedness (45%), and interactions (15%).

A complete sample of galaxies with properties similar to those of field galaxies has been imaged in the 21-cm line. So far, HI imaging surveys of field galaxies have been biased by strong selection criteria such as certain lower limits on the HI flux density or angular size, invoked to select observationally favorable systems. In our sample of Ursa Major galaxies, nearly all systems were imaged in HI regardless of their size and HI content. This strategy has lead to unbiased statistics of HI surface densities, frequency of lopsidedness, warps, and global kinematic perturbations. These statistics have not yet been fully explored and will be addressed in future studies.

4 The TF scatter and slope

- The origin of the scatter and the slope of the TF-relation has been investigated by using the shapes and amplitudes of the rotation curves in the outer parts of spiral galaxies – generally beyond the radii sampled with optical rotation curves.

We see that galaxies with rotation curves that are still rising at the last measured point lie systematically on the low-velocity side of the TF-relation while galaxies with a declining rotation curve tend to lie on the high-velocity side of the TF-relation when using $W_R$ or $V_{\text{max}}$. The main results are:

Scatter: No intrinsic scatter

Using $V_{\text{flat}}$ instead of the occasionally higher $V_{\text{max}}$ and excluding galaxies with rising rotation curves reduces the scatter in the TF-relation to values consistent with the observational uncertainties. The tightest correlation is found for the $K'$–$V_{\text{flat}}$ relation with a total observed scatter of 0.29 mag, a slope of $-10.3 \pm 0.4$, $\chi^2_{\text{red}} = 1.17$ and $\Gamma_{N-2} = 0.33$.

Slope: The slope of the TF-relation steepens progressively from the B-band ($-6.7 \pm 0.4$) to the $K'$–band ($-10.3 \pm 0.4$).

Assuming that low surface brightness and dwarf galaxies are relatively dust-free ($L_{\text{dwarf}}/L_B$ is small), thereby omitting internal extinction corrections for these systems, results in equal slopes of $\approx -10$ in all passbands when using $V_{\text{flat}}$.

One of the main results of the present work is that the observed scatter in the TF-relation can be largely understood in terms of the individual galaxy rotation curves. For convenience and simplicity we identified three basic shapes of rotation curves. First of all, there are the ‘classical’ rotation curves which rise gently near the center, smoothly turn over into the flat part and then remain flat out to the last measured point. Then there are the ‘rising’ rotation curves which in general turn over somewhat but not far enough to reach the flat part. These rotation curves are still rising at the last measured point and the observed maximum rotational velocity provides a lower limit on the actual maximum rotational velocity induced by the potential of the dark matter halo. These rotation curves are mainly found in the fainter dwarf galaxies and in galaxies without extended HI disks. Thirdly, there are the ‘declining’ rotation curves which rise very steeply near the center, reach their peak rotational velocity inside the stellar disk and then decline somewhat before they reach an extended flat part. For these ‘declining’ rotation curves a distinction can be made between the maximum rotational velocity $V_{\text{max}}$ and the amplitude of the outer flat part $V_{\text{flat}}$. This latter kind of rotation curves is mainly found in the brighter earlier type spirals with a compact distribution of the stellar component often identifiable with a bulge.

When the highest velocity, $V_{\text{max}}$, from the rotation curves is used, it turns out that all galaxies with ‘rising’ rotation curves lie systematically on the low-velocity side of the relation while galaxies with a ‘declining’ rotation curve tend to lie on the high-velocity side. Galaxies with ‘classical’ rotation curves define
a steeper relation with a smaller scatter than the full sample. Using \( V_{\text{flat}} \) instead of the occasionally larger \( V_{\text{max}} \) excludes galaxies with ‘rising’ rotation curves and shifts the galaxies with a ‘declining’ curve onto the relation defined by galaxies with a ‘classical’ rotation curve. Assuming that \( V_{\text{flat}} \) can be identified with the maximum velocity induced by the potential of the dark matter halo, we infer that the TF-relation is truly a relation between the luminosity of a galaxy and the maximum rotational velocity of the surrounding dark matter halo. It seems irrelevant how the luminous matter is distributed within that halo.

We also investigated, making use of the \( B, R, I \) and \( K' \) photometry, how the slope of the TF-relation varies as a function of passband. We find the well know effect that the relation steepens from \( B \) to \( K' \) where it reaches a slope of -10. We note, however, that the observables for all galaxies are corrected in the same way and that, in particular, the LSB galaxies receive the same correction for internal extinction as the HSB galaxies. This does not seem appropriate since the IRAS \( L_{60\mu m}/L_B \) ratio is much lower for the fainter LSB systems, indicating that the relative dust content of LSB galaxies is much lower than that of HSB galaxies. Assuming that the LSB galaxies in our sample are dust-free, we only corrected the HSB galaxies for internal extinction. Constructing the TF-relation under the assumption that LSB galaxies are transparent, we find that the slope in the relation is -10 for all passbands.

5 The shapes of rotation curves

- Roughly one-third of the observed HI rotation curves deviate noticeably from the ‘universal rotation curve’ shape.

The shapes of the rotation curves of kinematically unperturbed spirals were investigated as a function of galaxy morphology, surface brightness, scale length and compactness. In general, rotation curves of Sd/Sm galaxies are still rising at their last measured points, those of Sc systems are in general flat in the outer regions, while the rotation curves of Sa/Sb type galaxies may show a declining part. No declining rotation curves have been found below a maximum rotational velocity of \( \approx 150 \) kms. This is in accordance with the findings of Casertano and Van Gorkom (1991).

We have also qualitatively compared the shapes of the observed HI rotation curves to the shapes predicted by the ‘universal rotation curve’ (URC) as prescribed by Persic et al (1996). Roughly one-third of the observed rotation curve shapes deviate by more than the observational uncertainties from the URC shape. These deviations occur both in the inner regions and beyond about \( R_{80} \). Therefore, we conclude that the URC prescription in its present state is inadequate.

6 Dark matter in spiral galaxies

- The rotation curves have been decomposed adopting for the dark halo an isothermal sphere and a Hernquist density profile. The isothermal sphere models generally give better fits (lower \( \chi^2_{\text{red}} \)).

- In the isothermal sphere case, the near-infrared stellar mass-to-light ratios required for maximum-disk fits in high surface brightness galaxies are independent of color and galactic morphology and display a small scatter: \(<M_*/L_{K'}>=0.7\pm0.2\). For low surface brightness galaxies we find an average value of \(<M_*/L_{K'}>=1.3\) with a scatter of 0.5.

- The dark-to-luminous mass ratios within the last measured points of the rotation curves depend strongly on the adopted stellar mass-to-light ratios. Maximum-disk fits and equal-\( (M_*/L_{K'}) \) fits give contradictory results.

- The observed rotation curves of three galaxies with equal luminosities (i.e. equal \( V_{\text{flat}} \)) but with different surface brightnesses suggest that these three galaxies are embedded in the same isothermal dark matter halo, assuming they have nearly equal \( (M_*/L_{K'}) \) ratios.

The well resolved HI rotation curves of 22 spirals with unperturbed kinematics have been decomposed using the \( K' \) luminosity profiles. Two different models for the dark halo density profiles have been used: a modified isothermal sphere and a Hernquist halo. Four different fitting methods have been applied for both cases: a maximum-disk fit, a sub-maximum-disk fit, fits with equal-(\( M_*/L_{K'} \))=0.6 for all galaxies and constrained-halo fits. It turns out that the isothermal sphere model results in more satisfactory fits (lower \( \chi^2_{\text{red}} \)) than the Hernquist model, regardless of the fitting method. This is especially the case for LSB galaxies.

Maximum-disk fits to the rotation curves of HSB galaxies require near-infrared stellar mass-to-light ratios which show remarkably little variation from one galaxy to another. An average value of \(<M_*/L_{K'}>=0.7\pm0.2\) is found without any obvious trend with \( B-K' \) color or morphology. This argues in favor of a maximum-disk solution for HSB galaxies. Although much larger \( (M_*/L_{K'}) \) ratios are allowed by a maximum-disk situation in LSB galaxies, adopting equal \( (M_*/L_{K'})=0.6 \) values for LSB galaxies shows that these systems are dynamically dominated by dark matter at all radii.

In the case of a maximum-disk, the inferred structural properties of the dark halo are very uncertain. However, assuming equal-(\( M_*/L_{K'} \))=0.6 for
LSB galaxies implies that the observed rotation curve closely relates to the rotation curve of the dark halo. Consequently, the structural properties of dark haloes around LSB galaxies are reasonably well defined and we have found that LSB galaxies with smaller core radii have higher central densities.

We have found that conclusions on the dark-to-luminous mass ratios inside the last measured point of the rotation curve depend strongly on the applied fitting method. Equal-(M/L) and constrained-halo or maximum-disk fits lead to contradicting results.

Assuming equal-(M/L) for all galaxies we have found tentative evidence for a kinematic bimodality. Galaxies seem to avoid a situation in which the stellar disk and the dark halo are dynamically equally important near the radius where the rotation curve of the stellar disk peaks.

Finally, we have compared the rotation curves of three galaxies of the same luminosity, and hence with a similar Vflat, but with very different distributions of the stellar mass. Assuming that these three galaxies are embedded in the same isothermal dark halo, acceptable decompositions can be achieved with nearly equal (M/L) ratios for the stellar components. It seems that galaxies of the same luminosity can live in identical haloes, regardless of how the luminous mass is distributed.

7 Prospects for future research

The now available, observational data for the Ursa Major sample of galaxies provides a wealth of information for future research. At present, more data are being collected in the far-infrared with ISO and in the sub-mm regime with SCUBA on the JCMT. These new data will serve to investigate the possibility that large quantities of very cold but obscuring dust exist in low surface brightness and dwarf galaxies. A better understanding of the dust component of these galaxies is needed in order to evaluate whether the generally applied corrections for internal extinction in these systems are warranted.

One of the most intriguing and controversial results of this research is the apparent bimodal distribution in the K'-band surface brightness distribution. If real, this effect may provide hints about the stability of stellar disks in the present-day and during the epoch of their formation. In order to verify these results, it is necessary to have a carefully selected sample of galaxies without any particular emphasis on either high or low surface brightness systems. For instance, a volume limited, HI selected sample might be most appropriate for such a study. In fact, a continuous volume of roughly 130 Mpc³ within a high density region in one of the filaments of the Perseus-Pisces Supercluster has already been surveyed in HI with the VLA at nearly constant sensitivity. All galaxies detected in HI will be photometrically imaged in the near-infrared to determine their surface brightness profiles.

These same VLA data are of sufficient angular resolution to allow a crude determination of the shapes of the rotation curves. The main objective will be to determine whether the rotation curves are still rising, flat or declining at the last measured point. In combination with the K' photometry, the near-infrared Tully-Fisher relation will be constructed for this sample using less detailed information on the shape of the rotation curves. However, since the observed volume is at a five times larger distance than the Ursa Major cluster studied in this thesis, the depth of this sample will contribute less to the scatter and the issue of a possible intrinsic scatter in the TF-relation can be better addressed.

The present multi-band photometric survey of the Ursa Major cluster should also lead to a better understanding of the stellar populations of the various galaxies in this cluster. In combination with the observed deviations from the TF-relations in the optical passbands, it should be possible to put better constraints on the global stellar mass-to-light ratios. These constraints can in turn be very useful to obtain more reliable determinations of the structural properties of dark matter haloes around spiral galaxies.

In the future, the development of a high sensitivity (sub-)mm array will make it possible to obtain kinematic information at very high angular resolution using many diagnostic spectral lines. These capabilities ensure that a millimeter array would be a very powerful tool to study a wide variety of Galactic and extragalactic objects in great detail. A new and rich field of astronomical research would then be fully opened.