The ursa major cluster of galaxies
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Chapter 1

Introduction

ABSTRACT—The scope of the research presented in this thesis is twofold: 1) to investigate the statistical properties of the Tully-Fisher relation and 2) to study the properties of dark and luminous matter in spiral galaxies. The TF-relation and the properties of dark matter haloes are intimately related to each other. For this study we make use of detailed photometric and kinematic information of individual spiral galaxies obtained via optical and near-infrared photometric imaging and 21-cm line synthesis observations. We consider a complete sample of spirals in the Ursa Major Cluster of galaxies, intrinsically brighter than the SMC. Since all these galaxies are nearly at the same distance, there is little doubt about their relative luminosities, sizes and masses.

1 Tully-Fisher relations

The Tully-Fisher (TF) relation describes the well known, empirically established correlation between the intrinsic luminosity of a spiral galaxy and its rotational velocity (Tully and Fisher 1977). Two important aspects of the TF-relation make it one of the most widely studied and applied correlations in extra-galactic astronomy.

In the first place, it serves as an empirical tool to obtain accurate distances to spiral galaxies. The scatter in the TF-relation and consequently its usefulness as a precision distance estimator is, however, still a subject of debate. In the second place, the TF-relation results from the interplay between the various structural and dynamical components of a spiral galaxy, both in their present-day configuration and during the epoch of galaxy formation. As such, the observed TF-relation places strong constraints on galaxy formation theory. Especially the observed tightness of the correlation and the implied small intrinsic scatter provides a serious challenge for those who model and simulate the process of galaxy formation.

A large number of studies of the various aspects of the TF-relation have been carried out in the past two decades. Presenting a comprehensive overview of these investigations is beyond the scope of this introduction. See for instance Jacoby et al (1992, Section 7), Strauss and Willick (1995, Section 6.1.1) and Rhee (1996, Chapter 1) for overviews of the development of the TF-relation.

The strength of the present study follows from the combination of three observational aspects: 1) use of a well-defined complete sample of equidistant spirals in a cluster, 2) the availability of extended HI rotation curves for all spirals, and 3) B, R, I and, above all, K imaging photometry. In the following subsections, these three aspects are briefly described.

1.1 The importance of a proper sample

The properties of a sample of galaxies are of crucial importance for the study of the statistical characteristics (slope and scatter) of the TF-relation in the context of both its usefulness as a distance estimator and the origin of its observed and intrinsic scatter and slope.

For instance, if the TF-relation is to be used as a distance tool, one would preferably select regular, non-interacting, highly inclined and luminous Sc galaxies with steep HI profile edges. However, with such a restricted sample it would be impossible to properly address the issues related to the intrinsic scatter in the TF-relation. On the other hand, the accuracy with which cosmic velocity fields can be mapped by means of the TF-relation may be undermined by the inclusion of early type spirals and the faintest dwarf galaxies in the
analysis. For instance, Rubin et al (1985), using optical rotation curves, showed that a morphological segregation is present in the TF-relation in the sense that the zero point of the relation defined by early type spirals is offset to lower luminosities (or higher rotational velocities) compared to the zero point of late type spirals.

Furthermore, the derived statistical properties of the TF-relation may depend on the region of the universe from which the galaxies were selected. If galaxies from the nearby field are selected, distance uncertainties may be the dominant cause of scatter in the correlation. If, however, distances of nearby field galaxies are inferred from radial velocities by considering a model for the velocity field of the Local Supercluster, one is likely to find an artificially small scatter if this applied model velocity field itself is derived from TF distances. Moreover, the statistical properties of a field sample can be severely affected by the effects of a Malmquist bias and ingenious correction schemes have been developed to cope with these effects.

Many of these potential problems can be circumvented by selecting a complete sample of galaxies from a cluster. This procedure, however, has its own pitfalls. In the late eighties, the tightest correlations were found by using near-infrared luminosities for cluster samples. Scatters as low as 0.3 mag were reported by Pierce and Tully (1988) for the UMa cluster. Bothun and Mould (1987) found scatters of 0.20-0.25 mag for the more distant Pisces and A2634 clusters. Such low values imply relative distance uncertainties to individual galaxies of only 10-15%. These low scatters were disputed by Kraan-Korteweg et al (1988) who found for a sample of spirals in the Virgo cluster a scatter as large as 0.7 mag and a significant offset of the zero point. It was subsequently argued by Pierce and Tully (1988) that such an offset and large observed scatter is caused by severe background contamination in the region of the Virgo cluster which was confirmed by Pierce (1989) and Jacoby et al (1990). This illustrates that cluster samples with a large velocity dispersion should be avoided.

For our study we carefully selected a volume limited and complete sample of equidistant spirals from the Ursa Major cluster of galaxies at a distance of 15.5 Mpc with a velocity dispersion of only $150 \text{ km/s}$. Within a particular window on the sky and in recession velocity, 62 galaxies, intrinsically brighter than the SMC, make up a complete sample. Seventeen more dwarf systems are identified in this volume but these are fainter than our completion limit.

Another important issue is less related to the properties of a sample. The scatter in the TF-relation is mostly evaluated in terms of magnitudes and is thus related to the slope of the relation. Determination of this slope depends on the applied fitting method. Especially when the observed correlation is not very tight, performing direct, bi-sector or inverse fits to the same data points will result in different estimates of the total observed scatter. Consequently, a correlation with a larger scatter but with a steeper slope may still be tighter than a correlation with a lower scatter but with a shallower slope.

All the different sample selection and fitting procedures used by the various investigators make it practically impossible to consistently intercompare the results from the numerous studies of the TF-relation. It seems unlikely that in the near future a census will be reached on the statistical properties of the TF-relation.

### 1.2 The advantage of HI rotation curves

The rapid development of optical and near-infrared detector arrays has led to greatly improved measurements of the luminosities of spiral galaxies, ranging from the originally estimated photographic $B$ magnitudes (Tully and Fisher 1977) to the present-day high quality near-infrared surface photometry (cf. Peletier and Willner 1993 and Chapter 2 of this thesis). Relatively little attention, however, has been given to the meaning of the HI linewidth. To some approximation, the rotational velocity of a spiral galaxy might be determined from the properly corrected width of its global HI profile. Indeed, this might be the case if the rotation curve of the HI disk rises in the inner regions and levels off to a constant velocity in the extended outer parts. However, from HI synthesis mapping of spirals it has become clear that there are two basic deviations from this classical rotation curve shape.

First, many low surface brightness and dwarf galaxies only show the rising part of the rotation curve; the HI disks do not extend far enough to probe the regime of constant rotational velocity. Their observed maximum rotational velocity provides merely a lower limit to the actual maximum rotational velocity induced by the potential of their dark matter halo.

Second, the more massive and compact galaxies often show a steep rise of the rotation curve with a maximum in the optical region followed by a modest decline until the flat part is reached in the outer regions (cf. Casertano and Van Gorkom, 1991).

Furthermore, the width and shape of the global HI profile will also be affected by the distribution of the HI gas in the disk and the possible presence of a warp or non-circular motion. The present study is aimed at understanding the statistical properties of the TF-relation (tightness, scatter and slope) using knowledge of the detailed shape of the extended HI rotation curves.

In recent years, optical $H_\alpha$ rotation curves obtained from long-slit spectroscopy (e.g. Matthewson et al, 1992) or from Fabry-Perot mapping of galactic velocity fields (e.g. Schommer et al, 1993) has been used to evaluate the scatter in the TF-relations (e.g. Rhee,
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1996, Raychaudhury et al, 1997 and Courteau, 1997). However, applications of these techniques exclude low surface brightness (LSB) galaxies and do not allow the detection of possibly declining rotation curves beyond $R_{25}$. The more extended HI rotation curves, do not have these limitations.

1.3 Near-infrared photometric imaging

Apart from $B$, $R$ and $I$ photometric imaging, $K'$ near-infrared surface photometry is obtained for 61 of the 62 galaxies in the complete sample. The $K'$ photometry has two major advantages above optical photometry. First of all, the near-infrared light is hardly affected by internal and Galactic extinction. Consequently, any additional scatter in the observed TF-relation introduced by uncertain extinction corrections is minimized in the $K'$-band. Obvious dust-lanes in optical images of nearly edge-on systems are almost invisible at $K'$. Furthermore, it is a generally accepted idea that the near-infrared luminosity of a stellar population is more closely related to the mass locked-up in the stars than the optical luminosity. However, the near-infrared wavelength range is "not yet fully explored to study the stellar populations in the central parts of galaxies" (Leitherer et al, 1996).

2 Dark Matter in spiral galaxies

The second scientific driver for the present research is to obtain a better understanding of the structural properties of dark matter haloes and of the dark-to-luminous mass ratios as a function of the characteristics of the luminous mass in spiral galaxies such as bulge-disk ratio and surface brightness. For overviews on the topic of dark matter in spiral galaxies see for instance Trimble (1987) and Ashman (1992). Here, I will only discuss how the present study of dark matter in spiral galaxies using HI rotation curves, fits in past and present investigations which applied similar techniques.

2.1 Investigating dark haloes using HI rotation curves

Properties of dark matter haloes around spiral galaxies are usually derived from extended HI rotation curves which are decomposed into the contributions of the various dynamical components like a bulge (if present), stellar and gaseous disks and a dark matter halo. Since rotation curves are generically flat in the outer regions, dark matter haloes are in general modelled by an isothermal sphere, modified to have a roughly constant density within a certain core radius. The technique of decomposition then allows to adjust the mass-to-light ratios of the stellar components and the two parameters that describe the density profile of a modified isothermal sphere, i.e. the core radius and the asymptotic maximum rotational velocity.

What follows is a brief overview of the most elaborate studies of the properties of dark haloes using extended HI rotation curves.

Bosma (1981a,b) presented the first systematic study of dark matter in spirals using extended HI rotation curves. He obtained HI velocity fields of 6 spiral galaxies using the Westerbork Synthesis Radio Telescope (WSRT) and collected from the literature similar observations of 16 more spirals. From these observational results it became clear that rotation curves remained more or less flat until the last measured point which lies at many optical scale lengths from the center. Bosma also demonstrated that two-dimensional information on a galactic velocity field is necessary to detect possible deviations from circular motions and to assess the reliability of rotation curves obtained from (the radio equivalent of) long-slit spectroscopy along the optical major axis.

Carignan and Freeman (1985) discussed the dark halo parameters of dwarf galaxies using HI synthesis data of four systems. Because their observed rotation curves do not turn over into a flat part, they could infer only lower limits on the core radii and maximum halo velocities. However, from the well determined central densities of the dark haloes, they concluded that the dark-to-luminous mass ratio is comparable to those determined for the brighter Sc spirals.

Wevers et al (1986) obtained HI velocity fields of 16 more nearby spiral galaxies in the field. Their observed rotation curves were not analyzed in any detail. The existence of extended flat rotation curves as observed by Bosma and others was consolidated by Begeman (1987, 1989) who used the upgraded WSRT to obtain high quality rotation curves of 8 spirals including several of Bosma’s galaxies. Begeman further refined the technique of extracting rotation curves from galactic velocity fields by actually fitting tilted rings. The findings of Begeman’s thesis research and of other similar studies were presented in several high impact papers in the mid-eighties (van Albada et al 1985, van Albada and Sancisi 1986 and Sancisi and van Albada 1987). In these papers, the concepts of maximum-disk decompositions and the disk-halo conspiracy were established.

It was pointed out by Lake and Feinswog (1989) that the technique of decomposing the observed rotation curves does not put strong constraints on the structural properties of isothermal dark matter haloes. Most observed rotation curves can be well fitted by just an isothermal sphere model alone, i.e. the stellar $(M/L)=0$. On the other extreme, the stellar mass-to-light ratio can be increased until the rotation curve induced by the lu-
mous mass reaches the observed rotation in the inner region. This situation corresponds to a so-called maximum-disk fit (Sancisi and van Albada, 1987) and may result in unrealistic halo properties like a hollow core which should be carefully avoided. Clearly, the stellar mass-to-light ratios and the inferred halo properties are closely related and the two extreme cases sketched above merely provide upper and lower limits on the halo parameters. Additional contraints on the stellar mass-to-light ratios are required if trends in the structural properties of dark matter haloes as a function of luminosity, bulge-disk ratio and surface brightness are to be revealed.

Casertano and van Gorkom (1991) showed that massive high surface brightness galaxies with short scale lengths may show declining rotation curves in the outer regions. Their findings demonstrated that the disk-halo conspiracy, the interplay between luminous and dark matter which results in flat rotation curves, does not hold in these systems.

The thesis work of Broeils (1992) aimed at determining the properties of dark matter haloes using 12 spiral galaxies which cover a wider range of luminosities and morphologies than previous studies. Especially the earliest type spirals and the fainter dwarf galaxies had Broeils’s special attention. He adopted the maximum-disk approach when decomposing the rotation curves. The galaxies he selected were drawn from the nearby field and, unfortunately, the distance uncertainties to individual galaxies were quite significant.

Carignan, Puche and co-workers published a series of papers describing HI observations of six galaxies in the Sculptor group (Puche and Carignan 1991 and references therein). Their aim was to compare the dark matter content of individual galaxies to the dark matter content of the group as a whole. They concluded that the global dark-to-luminous mass ratio of the whole group was roughly ten times larger than that of individual galaxies.

Other extensive HI synthesis surveys of galaxies at approximately equal distances in the Virgo cluster were carried out by Warmels (1988) and Cayatte et al (1990) who observed 25 spirals with the VLA. Their data was of too low angular and spectral resolution to derive rotation curves suitable for decomposition (Guhathakurta et al 1988). Other HI synthesis surveys of rich cluster environments have been performed by McMahon (1993) of the Hydra cluster and by Dickey (1997) of the distant Hercules Supercluster. However, these surveys were not intended to study the dark matter contents of individual galaxies.

Coté (1995, 1996) focussed her thesis research on extremely faint dwarf galaxies and obtained detailed HI velocity fields for eight systems. Most of these galaxies are clearly supported by rotation and the dynamical importance of the dark matter increases toward lower luminosities.

In most recent years, low surface brightness galaxies have gained much interest. Their number, mass and luminosity densities as well as their evolutionary and dynamical status can put strong constraints on cosmological models and galaxy formation scenarios. De Blok et al (1996) and De Blok (1997) have obtained HI synthesis observations of a sample of 19 low surface brightness (LSB) galaxies. Pickering et al (1997) have obtained sensitive VLA observations of 4 giant LSB galaxies, including Malin 1. Because the HI surface densities in LSB disks are quite low, it is very difficult to determine reliable rotation curves for these elusive galaxies.

2.2 This thesis research

The selected sample of spiral galaxies in the Ursa Major cluster, used for this thesis research, has many advantages compared to samples used in previous studies:

1) All galaxies are at the same distance and consequently there is little doubt about their relative luminosities and masses.

2) All galaxies, intrinsically brighter than the SMC, are in a specified window on the sky and in redshift are selected. This ensures that the selected galaxies potentially cover a wide range of luminosities, morphologies and surface brightnesses.

3) Although this sample is at the same distance as the Virgo cluster, WSRT observations were performed at a four times better angular and spectral resolution than the VLA observations of Virgo spirals mentioned above.

4) K’ photometry is available for all galaxies brighter than the SMC. Relatively minor differences in the near-infrared stellar (M/L_K) ratios are expected. Assuming equal (M/L_K) ratios for all the equidistant spiral galaxies in the sample is probably the best approach when decomposing their rotation curves and investigating possible trends in the inferred halo properties. Note that the maximum rotational velocity induced by the stellar disk is proportional to \( \sqrt{M/L_K} \) and is thus not very sensitive to the anticipated small galaxy-to-galaxy variations in (M/L_K).

A potential disadvantage of this sample is that the galaxies were not selected for their regular morphology nor for a large HI content. Consequently, several galaxies may be unsuited to derive extended HI rotation curves.

In this study, the decompositions are not restricted to maximum-disk fits. As implied above, the rotation curves are also decomposed assuming equal (M/L_K) ratios for all galaxies. Furthermore, sub-maximum-disk fits and constrained-halo fits are performed as
well.

In recent years, the concept of a universal density profile for dark haloes has emerged from N-body simulations of galaxy formation (Navarro et al. 1996). In the radial regime where the rotation curves can actually be measured, this density profile of the dark halo closely resembles the so-called Hernquist profile (Hernquist 1990). Therefore, the rotation curves are also decomposed by adopting this analytical Hernquist model for the dark matter halo density profile. The isothermal sphere and Hernquist models are compared with each other in terms of how successful the observed rotation curves can be fit.

It is claimed by Persic et al. (1996 and all references therein) that the observed rotation curves also follow a particular universal shape as a function of luminosity. The shapes of the rotation curves of Ursa Major spirals are qualitatively compared to their prescription of this universal rotation curve shape.

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