# CHAPTER II

# Luminous and Dark Matter in Spiral Galaxies: A New Test

In almost all galaxy formation scenarios non-baryonic dark matter plays an important role. Today's numerical simulations of cosmological structure evolution reproduce fairly well the observed distribution of galaxy properties in the universe (e.g., Kauffmann et al. 1999) and attempts to model the formation of single galaxies have been made as well (Steinmetz & Müller 1995). In these simulations the baryonic matter cools and settles in the centers of dark halos where it forms stars. The distribution of stars and gas in a galaxy depends strongly on the local star formation and merging history. At the same time that the stars are forming the halos evolve and merge as well.

## 2.1. Maximal disks or not?

The final relative distribution of luminous and dark matter in the centers of the resulting galaxies is under debate because the mass distribution of the dark matter component is difficult to assess directly. Measuring luminous and dark matter mass profiles separately requires innovative strategies because the halo is poorly constrained and equally good fits to measured rotation curves can be achieved for a wide range of visible mass components (e.g., Broeils & Courteau 1997). In order to define a unique solution to this so called "disk-halo degeneracy", the "maximal disk" solution was introduced. It assumes the highest possible mass-to-light ratio (M/L) for the stellar disk (van Albada et al. 1985; van Albada & Sancisi 1986). A practical definition is given by Sackett (1997) who attributes the term "maximal" to a stellar disk if it accounts for 85% ± 10% of the total rotational support of the galaxy at $R = 2.2\ R_{\rm exp}$. This approach has proven to be very successful in matching observed H I and H$\alpha$ rotation curves (van Albada et al. 1985; Kent 1986; Broeils & Courteau 1997; Salucci & Persic 1999, Palunas & Williams 2000) and also satisfies some dynamical constraints, such as the criteria of forming $m = 2$ spirals (Athanassoula, Bosma & Papaioannou 1987) as well as observational constraints on the structure of the Milky Way (Sackett 1997). However, modern numerical N-body simulations find significant central dark matter density cusps (Fukushige & Makino 1997; Moore et al. 1999a). Even if the prediction of these strong density cusps may not be entirely correct, the simulations find that the dark matter is of comparable importance in the inner parts of galaxies (Blumenthal et al. 1986; Moore 1994; Navarro, Frenk & White 1996, 1997) and it thus has a considerable influence on the kinematics. In this case a stellar disk of a galaxy would turn out to be “sub-maximal”.

It is important to determine the relative proportion of dark and luminous matter in galaxies for a better understanding of the importance of the baryonic mass in the universe. This proportion also bears information on the dynamics and structure of the dark matter itself. Spiral galaxies are well suited to study dark matter distributions because their distinctly ordered kinematics provide an excellent tracer of the gravitational potential in the disk plane. Since bars in galaxies are very prominent features with distinct dynamic characteristics, they are especially well suited to evaluate the amount of luminous matter. Sophisticated studies of barred galaxies indicate that their stellar disks alone dominate the kinematics of the inner regions – the stellar contribution is maximal (Debattista & Sellwood 1998, 2000; Weiner et al. 2001a). However, studies of our own Milky Way, found also to be a barred spiral, still do not give a clear answer as to whether the disk is maximal (Sackett 1997; Englmaier & Gerhard 1999) or not (Kujiken 1995; Dehnen & Binney 1998).

Bottema’s analysis of the stellar velocity dispersion in various galactic disks led to the conclusion that disks cannot comprise most of the mass inside the radial range of a few exponential scale lengths (Bottema 1997). Aside from the dynamical analysis of single systems, other attempts to tackle this problem have been undertaken. Maller et al. (2000) used the geometry of gravitational lens systems to probe the potential of a lensing galaxy. They concluded that a maximum disk solution is highly unlikely. Courteau & Rix (1999) applied statistical methods to learn about the mass distribution in galaxies. In their analysis they found no dependence of the maximum rotation velocity on a galaxy’s disk size. The conflicting findings of different studies leave the question of the relative proportion of dark and luminous matter in galaxies still open.

## 2.2. The concept

In this thesis the fact is exploited, that the stellar mass in disk galaxies is often organized in spiral arms, thus in kinematically cold non-axisymmetric structures. In the canonical CDM cosmology the dark matter is collisionless and dominated by random motions. Although the introduction of weakly self-interacting dark matter was proposed to avoid current shortcomings of the CDM model (Spergel & Steinhardt 2000) it seems to raise other, comparably severe problems (Yoshida et al. 2000; Ostriker 2000; Miralda-Escude 2002). Hence it seems reasonable to assume that CDM is not substantially self-interacting, but dynamically hot and therefore not susceptible to non-axisymmetric spiral or other small scale structure.

In light of this, the key to measuring the baryonic and dark matter mass fractions is to make use of the non-axisymmetric structure that can be observed in the stellar light distribution. Using deviations from axisymmetry of stellar disks, several efforts have already been made to constrain the dark matter content of non-barred spiral galaxies (e.g., Visser 1980; Quillen 1999, and references therein). Some of the most significant conclusions came from studies of massive bars, which are the strongest non-axisymmetric structures in disk galaxies. Spiral arms comprise a less prominent, but still significant mass concentration. Already very early theoretical calculations of gas shocking in the gravitational potential of a spiral galaxy (e.g., Roberts 1969) came to the conclusion that “velocity wiggles” with

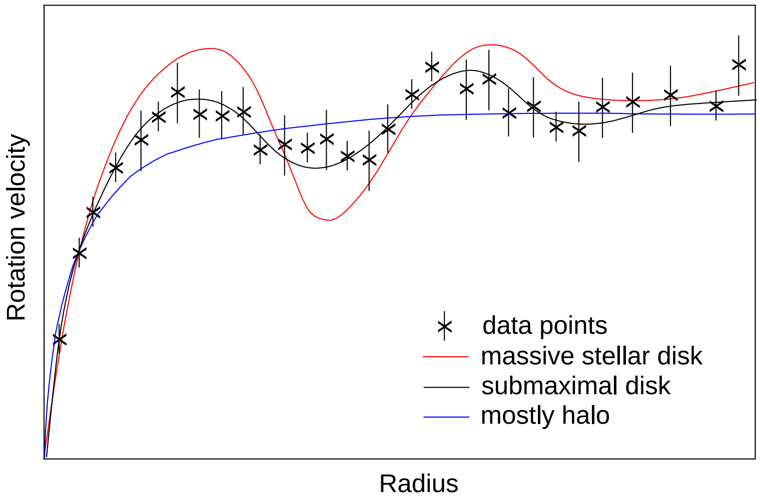

**Figure 2.1** Idea of the project. The measured gas velocity field (fictional data points) should be matched by a modelled gas velocity field from hydrodynamical simulation (continuous lines). The mass fraction of the non-axisymmetric stellar mass contribution determines the amplitude of the "velocity wiggles" in the simulations and is adjusted to match the observations. In the depicted scenario a submaximal disk (black line) yields the best fit to the data.

an amplitude of 10 to 30 $\mathrm{km\,s^{-1}}$ could be expected while crossing massive spiral arms. For ionized gas, measurements of the velocity to this precision can be achieved with common longslit spectrographs. The imprint of the spiral pattern in the velocity field of observed galaxies is indeed not very strong, as apparent in the 2D velocity fields of M 100 (Canzian & Allen 1997), of low surface brightness galaxies (Quillen & Pickering 1997) or of a sample of spiral galaxies (Sakamoto et al. 1999). There are only a few spiral galaxies without bars that show stronger wiggles in the velocity field that are associated with the arms, e.g., M 81 (Visser 1980; Adler & Westpfahl 1996) and M 51 (Aalto et al. 1999).

In order to still achieve the goal of measuring mass-to-light ratios it is needed to compare the expectedly weak features in the measured velocity field to detailed kinematic models. The use of new high resolution $K$-band photometry to map the stellar component and the application of a modern hydro-code to simulate galactic gas flows establishes a sound basis for the models to show enough details and enable the measurement of mass-to-light ratios. If the arms are a negligible mass concentration relative to the dark matter distribution in the galaxy, these wiggles should appear only very barely in the velocity field. The main aim of this project is to find out what fraction of the rotation speed comes from a mass component with spiral arms. In order to do this the strength of the wiggles in a galaxy's observed velocity field have to be compared to a model of the gas velocity field arising in a potential whose disk-halo fraction is known. As input for the gas dynamical simulations, it is necessary to derive the stellar potential of the galaxy from color-corrected $K$-band photometry, while the dark matter component is modelled as an isothermal sphere with a core. Simulations are performed for a variety of potential combinations and values for the pattern speed of the spiral structure. The results from these simulations are then compared to the observed kinematics.

## 2.3. The spiral structure of galaxies

For the present analysis the key element is the non-axisymmetric spiral structure observed in the stellar and gaseous components of many disk galaxies and the way it is depicted in their velocity fields. Understanding the basics of spiral morphology is essential in order to apply the appropriate modelling process. In this Section I briefly review the relevant concepts. For a thorough introduction in the field see Athanassoula (1984).

The spiral structure is closely related with the global dynamics of disk galaxies. Due to the differential rotation in the disk, a once established spiral would wind up into a very tight curl within a few dynamical time scales. Thus, the observed spirals cannot comprise of an aligned, fixed population of stars, but rather involve all stars maintaining a “kinematic density wave” in the disk. The spiral arms appear in domains, where the stars are packed more densely and move slower on their orbits. The density wave also induces shocks in the interstellar medium, causing star formation along the spiral arms. Under these circumstances, the newly formed stars make the spiral arms to appear bluer than the inter-arm regions. However, grand design spirals are not the product of a self propagating star formation wave as suggested by Gerola & Seiden (1978). This becomes apparent from NIR imaging, mainly tracing the old stellar populations, where the spiral arms are still clearly visible.

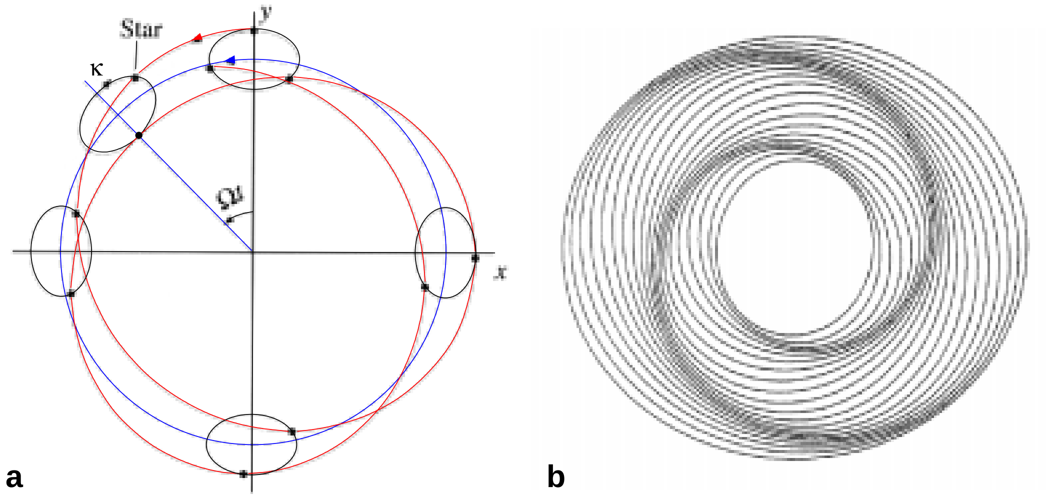

**Figure 2.2** The principles of spiral structure. **a)** In an inertial reference frame (x,y) a star’s orbital motion can be imagined as being a combination of a retrograde orbit about an epicycle with frequency $\kappa$ and the prograde orbital motion (blue line). In this reference frame the star’s path forms a non-closing rosette pattern (red curve). **b)** Nested oval orbits with a relative phase shift, as seen in a non-inertial reference frame rotating the global angular pattern speed $\Omega_{\rm p}$, can result in a grand design spiral density wave. Adapted from Carroll & Ostlie (1996)

The principles of a spiral density wave were developed by B. Lindblad and J. Oort in the mid of last century, namely the epicycle theory. In an inertial reference frame a star’s orbital motion can be described by its circular motion of frequency $\Omega$ around the galactic center, superposed with an oscillation of frequency $\kappa$ around the guiding center. In this “epicyclic approximation”, stellar orbits generally follow a non-closing rosette trajectory in the galactic disk (see Figure 2.2a).

However, for a variety of applications it is useful to introduce some non-inertial reference frame, rotating with an orbital frequency $\Omega_{\mathrm{p}}$. The advantage of this reference frame is, that $\Omega_{\mathrm{p}}$ can be chosen such that the orbit of the star is closed. For nearly circular orbits the requirement for a closed orbit is fulfilled, when $(\Omega - \Omega_{\mathrm{p}})/\kappa$ is rational:

$$\Omega_{\mathrm{p}}(R) = \Omega(R) - \frac{n}{m}\kappa(R). \quad n \text{ and } m \text{ are integers.} \tag{2.1}$$

While for most values for $n$ and $m$ $\Omega - \frac{n\kappa}{m}$ varies rapidly with radius, for $n = 1$ and $m = 2$ it is relatively constant across much of the galaxy. In this scenario, the orbits of the stars as seen from the rotating reference frame are ellipses. If these orbits are nested and aligned in a collective manner across the disk, different wave patterns can be created (see Figure 2.2b). As viewed from an inertial frame the pattern retains its morphology, but rotates with the angular frequency $\Omega_{\mathrm{p}}$. Thus, $\Omega_{\mathrm{p}}$ is called the pattern speed.

In the 1960s Lin and Shu (1964, 1966) developed the more elaborate quasi-stationary, linear density wave theory (for a review, see Bertin & Lin 1996). In this approach the spiral density wave is described as a the most unstable oscillation mode of the galactic disk. The amplitude of the spiral pattern evolves by interactions of these modes with the dissipative character of the interstellar medium. The stellar spiral pattern extends in the radial range between the inner Lindblad resonance (ILR) and the corotation if they are stationary. If they are growing they can extend even out to the outer Lindblad resonance (OLR) (e.g., Lin et al. 1969; Toomre 1981; Bertin et al. 1989a,b). The ILR and OLR are resonances between the epicyclic precession frequencies $\Omega \pm \kappa/2$ and the pattern speed $\Omega_{\mathrm{p}}$.

Due to the stability of the spiral structure resonances play a crucial role also for the morphological appearance of the galaxy. For example at the corotation radius, where the pattern speed $\Omega_{\mathrm{p}}$ is equal to the orbital frequency $\Omega$, the response of the gas is not periodic since the gas rotates along with the spiral perturbations and thus the non-axisymmetric forcing vanishes. In light of this, it is expected that at the corotation radius star formation cannot get excited by the density wave and should not be observed in a quiescent galaxy. The location of this resonance should become visible as a ring of largely reduced star formation (Shu et al. 1973).

However, in real galaxies the situation seems to be more complicated. In normal spiral galaxies with relatively open spirals, orbits belonging to the main orbital families deviate significantly from circular orbits, with the consequence that non-linear effects become important. The importance of non-linear effects in realistic models of spiral galaxies was studied by Contopoulos & Grosbøl (1986, 1988) and Patsis et al. (1991). It was found that at least for late type spiral galaxies, non-linear effects cause the response density to grow out of phase with the underlying potential already inside corotation and consequently the strong part of the spiral terminates at the 4/1 resonance, that is located roughly half way to corotation. If, however, the potential perturbation is weak, non-linear effects play a minor role. It is very difficult to settle these issues on an observational basis, since the locations of the resonances are generally not very well known for real galaxies.

Besides retaining the morphological shape of the spiral pattern, the question must be assessed on how the spiral maintains the amplitude of the density wave. Like any other wave travelling through a medium, also the spiral density wave needs to get regenerated continuously, or at least at certain times, to prevent it from dispersing and fading away. One internal mechanism has been proposed for galaxies that is referred to as swing amplification (Toomre 1981). If the pattern speed $\Omega_\mathrm{p}$ is high enough that no ILR is present, density waves can travel through the center of the disk, changing from a trailing to a leading spiral. Due to the differential rotation in the disk, the leading wave, propagating outwards towards corotation gets converted into a trailing wave. During this process the wave can get amplified by a factor 10 or more. If the swing amplification is not embedded into a feedback cycle, the mechanism would not provide a quasi-stationary spiral pattern.

Another internal mechanism to drive a spiral pattern is a central bar or oval asymmetry. Indeed, it has been found that already in simple models central bars can induce strong spiral features in the disk (Sanders & Huntley 1976). Important for the bar driving mechanism is a dissipative interstellar medium. Modern analyses find that the induced spiral structure depends on the rotation speed of the bar. Spirals associated with the outer Lindblad resonance, i.e. for fast bars, are tightly wound, while those associated with the inner Lindblad resonances for slow bars are relatively open (Yuan & Kuo 1997).

Finally, tidal interaction due to a companion galaxy's flyby may enhance the spiral density wave (Toomre 1974). During the flyby angular momentum is exchanged between the companion and the wave. As observed in the prominent examples of M 51 and M 81, the spiral pattern, driven by external tidal interaction, might result in very regular grand design structure. The tidal forcing depends strongly on the orbital parameters of the flyby. It matters, for example, if the companion orbits prograde or retrograde (Athanassoula 1978). Furthermore, the companion must pass fairly fast and close to have a noticeable effect on the spiral's disk morphology (Howard et al. 1993). To assure a tidally driven quasi-stationary spiral pattern, the companion must orbit very closely around the galaxy. However, this scenario would also only work for a limited time because on a closeby, periodic orbit the companion is predestined to merge with the spiral galaxy.

There are even more scenarios that have been proposed to cause or maintain spiral structure. Nevertheless, the spiral structure of a real galaxy in the universe is the product of several, simultaneously acting physical mechanisms. For selected objects one particular process might play a dominant role. These galaxies may then be considered as test cases for that specific theory. For the present project, the primarily important criterion is a strong spiral pattern. Its origin or driving process is a different issue.