Measuring Stellar and Dark Mass Fractions in Spiral Galaxies

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Abstract. We explore the relative importance of the stellar mass density as compared to the inner dark halo, for the observed gas kinematics thoughout the disks of spiral galaxies. We perform hydrodynamical simulations of the gas flow in a sequence of potentials with varying the stellar contribution to the total potential. The stellar portion of the potential was derived empirically from K-band photometry. The output of the simulations – namely the gas density and the gas velocity field – are then compared to the observed spiral arm morphology and the Hα gas kinematics. We solve for the best matching spiral pattern speed and draw conclusions on how massive the stellar disk can be at most. For the case of the galaxy NGC 4254 (Messier 99) we demonstrate that the prominent spiral arms of the stellar component would overpredict the non-circular gas motions unless an axisymmetric dark halo component adds significantly in the radial range $\mathrm{R_{exp}} < \mathrm{R} < 3\,\mathrm{R_{exp}}$.

1 Introduction

In almost all galaxy formation scenarios, non-baryonic dark matter plays an important role. Today's numerical simulations of cosmological structure evolution quite successfully reproduce the observed galaxy distribution in the universe [3]. While galaxies form and evolve inside dark halos their physical appearance depends strongly on the local star formation and merging history. At the same time the halos evolve and merge as well. According to the simulations, we expect that the dark matter is important in the inner parts of galaxies [5],[6] and that it thus has a considerable influence on the kinematics. These predictions are in contrast to some studies which indicate that galactic stellar disks - at least of barred spiral galaxies - alone dominate the kinematics of the inner regions [1]. Apparently this is also the case in our own Milky Way [2].

Determining individual mass fractions of the luminous and dark matter is not a straightforward task. The rotation curve of a disk galaxy is only sensitive to the total amount of gravitating matter, but does not allow the distinction between the two mass density profiles. For a detailed analysis it is necessary to adopt more refined methods to separate out the different profiles. Previous investigations used for example knowledge of the kinematics of rotating bars [8] or the geometry of gravitational lens systems [4]. Here we would like to exploit the fact, that the stellar mass in disk galaxies is often organized in spiral arms, i.e. in coherent non-axisymmetric structures. In most proposed scenarios, the dark matter, however, is collisionless and dominated by random motions. Therefore it is not susceptible to spiral structures. If the stellar mass dominates,

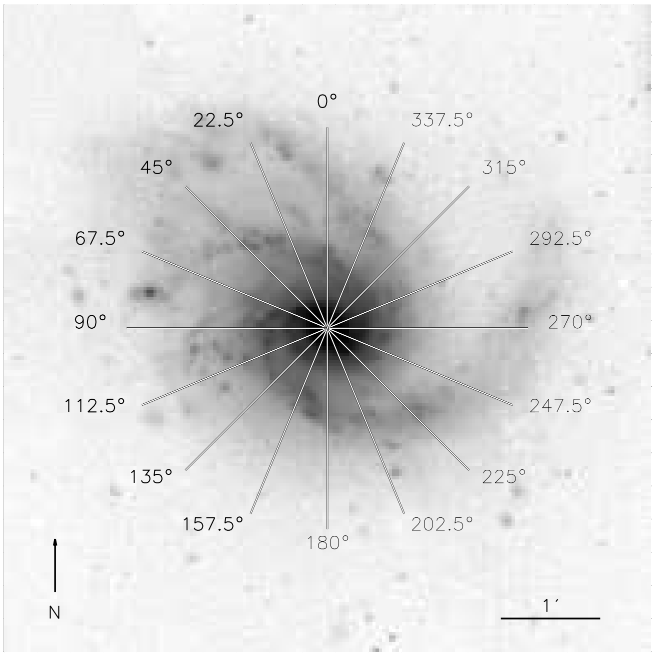

Fig. 1. Near infrared K'-band (2.1 μm) image of NGC 4254 with a total exposure time of 20 minutes at the Calar Alto 3.5 m telescope. Bright foreground stars are masked out. The overlay shows the slit orientations of the spectrograph. We took 8 longslit spectra (angles labeled in bold font) crossing the galaxy's center to measure the 2D velocity field

the spiral arms, as traced by the near infrared (NIR) light, should induce considerable non-circular motions in the gas, that manifest themselves as velocity "wiggles" in observed gas kinematics. Using hydrodynamical gas simulations we are able to predict these velocity wiggles and compare them to the observations. Hence the contribution of the perturbative forces with respect to the total forces can be determined quantitatively and can be used to constrain the stellar disk to halo mass ratio.

2 Observations

For this analysis we need data to provide us with information on the stellar mass distribution and on the gas kinematics of a sample of galaxies. To map the stellar surface mass density it is most desirable to take NIR images of the galaxies, because in this waveband dust extinction and population effects are minimized [7]. During two observing runs in May 1999 and March 2000, we obtained photometric data for 20 close-by NGC galaxies. We used the Omega Prime camera at the Calar Alto 3.5 m telescope with the K-band filter (K' at

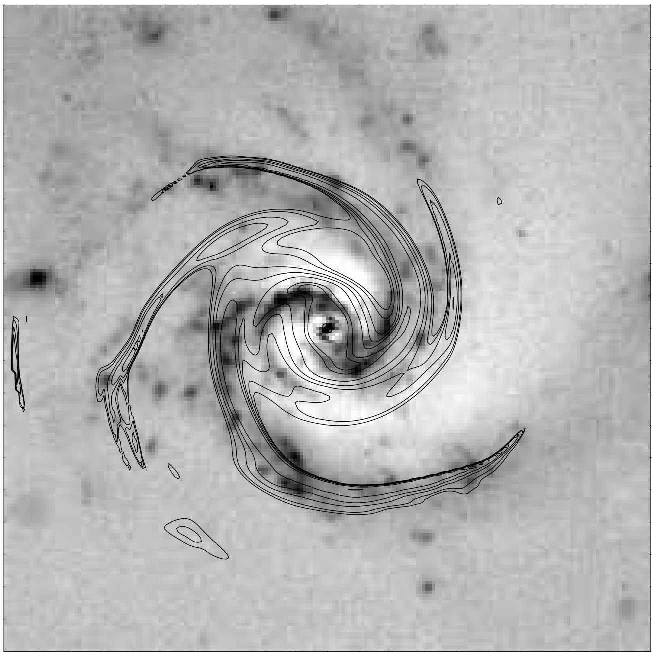

Fig. 2. Simulation results for the gas density. Here we depict the best fitting result (in contours) overlaid on a deprojected image of NGC 4254. To enhance the contrast of the spiral arms, an axisymmetric model of the galaxy has been subtracted from the original image. We find an excellent match to the spiral morphology

2.1 μm). It provides us with a field of view of 6.′76 x 6.′76. Figure 1 shows the K-band image of the Messier galaxy M99. The labeled one arcminute scale bar translates to 5.8 kpc within the galaxy.

The kinematic data were obtained with the TWIN, a longslit spectrograph at the 3.5 m telescope. For a reasonable coverage of a galaxy's velocity field, we needed to take 8 slit positions (or 16 position angles) across the entire disk of the galaxy (also displayed in Figure 1). We chose longslit-spectroscopy rather than fabry-perot interferometry because of its higher spectral resolution and better sensitivity to faint emission. So far we were able to collect complete sets of longslit spectra for only four galaxies, mostly due to only moderate weather conditions during the spectroscopy runs.

3 First results

As a pilot project, we analyzed the data of NGC 4254 (M99), a late type spiral galaxy with strong arms, located in the Virgo cluster. Assuming a constant stellar mass-to-light ratio in the K-band image, the gravitational potential due to the stellar mass fraction was calculated by direct integration over the whole

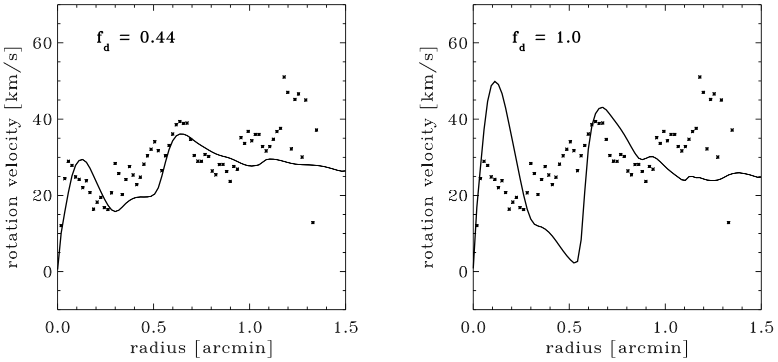

Fig. 3. Simulation results of the gas velocity. Here we compare two simulations (continuous lines) with different disk mass fractions $f_d = M_{disk}/M_{maxdisk}$ to the observed kinematics (data points). The maximal disk case (right) is clearly not matching the observations well. Displayed is only one (135°) out of 16 slit position angles

light/mass distribution. The mass-to-light ratio for the maximum disk contribution was scaled by the measured rotation curve. For the dark matter contribution we assumed an isothermal halo with a core. To combine the two components we chose a stellar mass fraction $f_d = M_{disk}/M_{maxdisk}$ and added the halo with the variable parameters adjusted to give a best fit to the rotation curve. We used this potential as an input for the hydrodynamical gas simulations.

Figure 2 presents the resulting gas surface density, as it settles in the potential. The morphology of the gas distribution is very sensitive to the speed with which the spiral pattern of the galaxy rotates (pattern speed). In figure 2 we printed the result of the simulation whose spiral structure best matches the K-band image morphology. We find quite good agreement for a pattern speed of $\Omega_p = 23\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, which places the corotation radius to 8.4 kpc.

To quantify the relevance of the stellar mass component, we need now to fit the velocities – in particular the amplitude of the wiggles. In figure 3 a comparison of the modelled and the measured rotation curves are presented for the position angle of 135°. The two panels show the rotation curves for different disk mass fractions: less than half maximal and the maximum disk case.

4 Discussion and outlook

Although there is quite some scatter in the observed gas kinematics, we find that the velocity jumps, which are apparent in the simulations for the maximum disk case are too large to be in agreement with the measurements. The inner part of the simulated rotation curve ($< 0\overset{\prime}{.}3$) is dominated by the dynamics of the small bar, which is present at the center of the galaxy. Its pattern speed might be different from the one of the spiral's and thus relate to a mismatch in the inner part of the rotation curve. We conclude that an axisymmetric dark halo is needed to explain the kinematics of the stellar disk. The influence of the stellar disk is submaximal in the sense that we don't find strong enough velocity wiggles in the observed kinematics as would be expected if the stellar disk was the major gravitating source inside the inner few disk scale lengths. How this conclusion might apply to other spiral galaxies will be the upcoming issue of this project. We plan to extend our analysis at first to the 3 other galaxies where we have already now complete data sets. Finally we intend to draw our final conclusions on a basis of a sample consisting of 8 - 10 members. This should be sufficient to determine reliable results about the luminous and dark mass distributions in spiral galaxies.

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