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BARYONIC MASS IN NEARBY GALAXIES (PHD THESIS)

MILENA JOVANOVIĆ
Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
E–mail: milena@aob.rs

Abstract. In my doctoral research, I utilized high-resolution observations from the HI Nearby Galaxy Survey (THINGS) to model the dynamical and baryonic mass distributions of nearby galaxies. These observations of neutral atomic hydrogen, boasting extensive data, enabled us to extract the rotation curve, thereby deducing the total dynamical mass up to a significant radius. In conjunction with infrared observations, we concurrently fit the dynamical mass with the observed stellar mass, the neutral gas component, and various dark matter (DM) models. The stellar mass was adjusted using the mass-to-light ratio, a critical factor in our study. We describe the DM component within the ΛCDM framework, using two distinct profiles: the pseudo-isothermal sphere and Navarro-Frenk-White. With the values for dynamical, stellar, gas, and dark matter mass determined, we derived assorted mass functions and distribution functions for our sample. From all the distribution functions we only present and discuss the distribution of the mass-to-light (M/L) ratio in detail here. The parameter is crucial for calculation of baryonic mass since it connects the observable quantities with the stellar (and consequently baryonic) mass required by dynamical models.

1. INTRODUCTION

This work is aimed at giving a brief overview of my PhD thesis, without going into specific results, that are the subject of future publications. The thesis focused on the dynamical modeling of proximate galaxies observable through HI emission. The neutral hydrogen line at 21 cm (HI) serves as a particularly convenient spectral line for probing the overall gravitational potential due to its large filling factor, widespread distribution in late-type galaxies, and the extension of HI disks to large radii.

Dynamical modeling seeks to improve the accuracy of determining galaxies' baryonic and dynamical masses, ensuring consistency between them. Mass, besides being a fundamental parameter in describing astrophysical objects, is also considered a significant driver of galaxy evolution. The distribution functions of mass provide a stringent test for current models of cosmology, structure formation, and scaling relations.

The THINGS sample (Walter et al. 2008, de Blok et al. 2008) was employed for this study. When imposing constraints, this sample is reduced to 20 galaxies located at distances between 4 and 15 Mpc. The sample exhibits significant variations in size, morphology, and brightness, with the absence of early-type and Sph galaxies, given their lack of HI gas.

Baryonic mass was determined using two different values of the mass-to-light (M/L) ratio for all galaxies in the sample, in conjunction with dynamical, stellar, and neutral gas masses, along with appropriate fractions.

The primary goal of deriving distribution functions, with the Baryonic Mass Function (BMF) as the most important one, was successfully achieved. This allows a comparison with BMFs determined for larger samples and an assessment of the quality and applicability of this in-depth analysis. Additional results in the thesis include discussions on the typicality of our galactic environment and the insights its evolutionary history can provide.

2. METHODS

For the purpose of dynamical modeling, the derivation of the rotation curve (RC) constitutes a crucial step. As previously mentioned, our RCs are constructed based on the THINGS HI data obtained using the *Very Large Array* (VLA) telescope. The components utilized to reproduce the observed RCs encompass stellar, cold gas, and dark matter (DM). The stellar component is based on observations in the 3.6-micron band, conducted as part of the Spitzer telescope S4G survey or, alternatively, extracted from the observations available at *Spitzer Heritage Archive* (SHA). The gaseous component is derived from the THINGS survey, with scaling applied to incorporate additional neutral species. DM is represented by two prevalent models: the pseudo-isothermal sphere (ISO, Jimenez et al. 2003) and the Navarro, Frenk, and White profile (NFW, Navarro et al. 1997), both part of the ΛCDM framework.

The RCs were derived using the *Groningen Image Processing System*[1] (GIPSY) software by fitting the center of the HI line in each point across the entire image of the gas disk. The fitting typically involves utilizing Gauss-Hermite polynomials. In cases where non-circular motions were prominent in the disk, a new procedure was devised. Once the typical velocity of the gas mass associated with each point on the gas disk is determined, i.e. the velocity field, the radial profile of the circular velocity in a disk, constituting the RC, is extracted through iterative fitting.

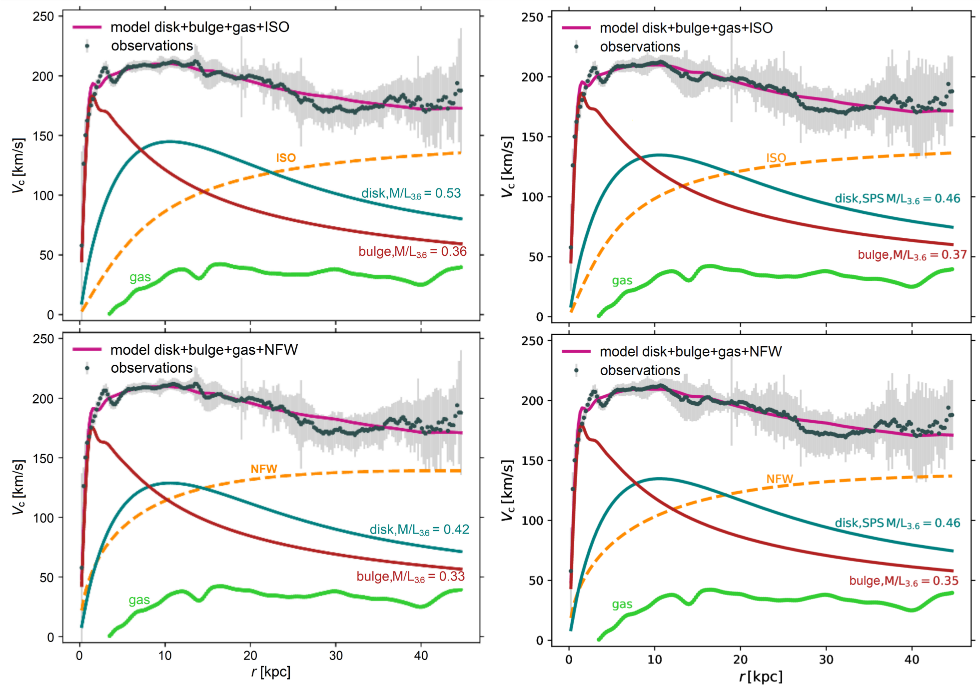
The stellar component is modeled by decomposing the resolved near-infrared (NIR) light into an exponential disk and a Sérsic-type bulge, particularly effective for disk-like galaxies. The gaseous component is derived from the integrated HI flux and subsequently scaled to account for other neutral species. Molecular gas is presently excluded, though it is believed to have a negligible impact on the overall mass of the galaxy. The selection of the DM profile was not the primary focus of this study; hence, the two most common density profiles, ISO and NFW, were employed. The former is often considered observational-based, while the latter is theoretically based and aligns with cosmological simulations. The combination of all components is intended to reproduce the observed RC (directly translated to dynamical mass) if the modeling is successful. Further procedural details are available in Samurović et al. 2015, Jovanović 2017, and Jovanović et al. 2021.

3. RESULTS

3. 1. DYNAMICAL MODELS

The incorporation of the M/L as a scaling factor for the stellar component constitutes a crucial aspect of this methodology. Two distinct sets of models were implemented: one where the M/L parameter was treated as a free variable, and the other employing M/L values derived from stellar evolutionary models, denoted herein as Stellar Population Synthesis (SPS) models. This, combined with the inclusion of two dark matter (DM) profiles, results in four sets of dynamic modeling procedures conducted

[1]`https://www.astro.rug.nl/~gipsy/`.



(a) free M/L (b) SPS M/L

Figure 1: Dynamical modeling of the observed NGC5055 RC (dark-gray circles) with galaxies' components: stellar disk (solid teal line), stellar bulge (deep red solid line), gas (green circles) and two DM profiles (dashed orange line) - ISO upper panels, NFW lower panels.

for the entire sample. Fig. 1. shows an example of four dynamical models for the large spiral NGC5055 galaxy, with two DM profiles and two M/L.

When leaving the M/L parameter free we effectively choose a dynamical model that is the best fit between stellar (primarily stellar disk component) and dynamical mass, together with gas and DM. The distribution of the free M/L can be used to find one overall value of the parameter, specifically for stellar light at 3.6-microns denoted as $M/L^{3.6}$. The ideal would be to, using theory and comparably detailed observations through a similar modeling, find one standard M/L value that describes stellar disks in disklike galaxies ($M/L^{3.6}_{disk}$), or alternatively, one value that fits best for galaxies grouped by size, morphology or type. The modeling procedure was successful for every galaxy in the sample, especially using ISO DM profile, where the quality of the fits was the best across all four sets of models. Still, the value prefered by our models differed to what is available in the literature so far (Meidt et al. 2014, Querejeta et al. 2015). Effects of dust were also accounted for in subsequent analysis which expectedly raised the overall M/L but is still not as high as noted by mentioned authors.

The best SPS-based M/L value for every galaxy was found in a manner described in Jovanović (2017). Based on a specific galaxy's metallicity and colors, 19 SPS models based on 4 Initial Mass Functions (IMF) were employed to infer M/L values

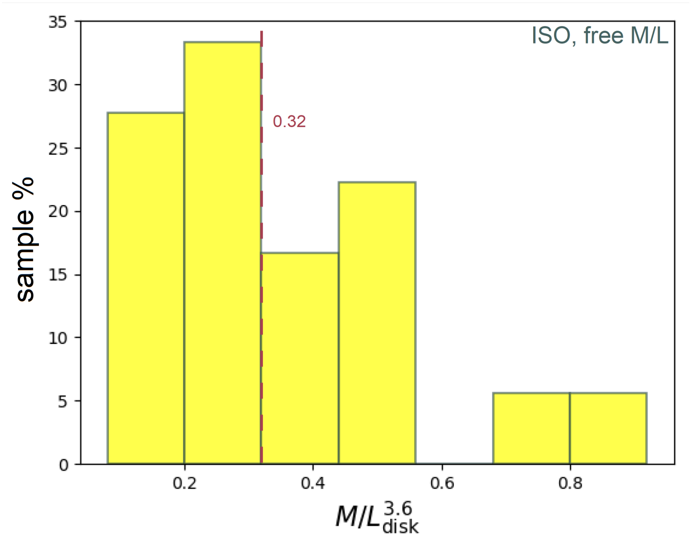


Figure 2: $M/L^{3.6}_{disk}$ from dynamical models with ISO DM profile and free $M/L^{3.6}_{disk}$ across the sample of galaxies, with 'best' value of 0.32 denoted by the red dashed line.

and construct histograms (with approximately 30 SPS model values), which then helped us determine one 'most-likely' value of M/L. M/L was then fixed to this best value in the second set of dynamical models. In some cases it was not possible to infer M/L, and in some cases it yielded nonsensical results in dynamical modeling. In this manner we were able to derive plausible M/L for 16 galaxies, and, from that, we fitted RCs for all of them.

3. 2. MASS-TO-LIGHT RATIO

The analysis of the distribution of the $M/L^{3.6}$ ratios of the disk enabled a comparison between models and with results from the literature. In the case of models incorporating a free M/L ratio alongside an ISO profile, the mass-to-light ratio at a wavelength of 3.6 microns for the disk component spans a range from 0.08 to 0.92, with a median value of 0.32. The distribution of the M/L_{disk} ratio for the free ISO model (Fig. 2) indicates clustering around the value of 0.32, which is deemed representative of the M/L ratio derived from this specific model. Models featuring a free M/L ratio coupled with an NFW profile yield a spectrum of $M/L^{3.6}$ disk ratios ranging from 0.06 to 0.90, with a median of 0.22, effectively capturing the observed clustering patterns evident in the corresponding histogram, which we do not show for brevity.

For Stellar Population Synthesis (SPS) models, the distribution of the $M/L^{3.6}_{disk}$ ratio is identical for both dark matter profiles since this parameter is fixed. The M/L ratio spans values from 0.05 to 0.59, with a median of 0.31. The corresponding histogram (not shown for brevity) shows no significant clustering, indicating that all values in the range occur with similar frequency.

The obtained distributions of the $M/L^{3.6}_{disk}$ ratios for all dynamic models revealed no clustering based on morphology (e.g., irregular or spiral). No dependence or preference for the M/L value was observed when considering galaxy size, using the dimensions of the gas disk (i.e., the last radius for which a rotation curve could be derived). There is no apparent regularity in the change of dynamic mass with a change in the M/L ratio.

Dust radiates precisely in the near-infrared region of the spectrum, so a portion of the light at 3.6 microns originates from it. The assessment of dust presence is based on the [3.6]-[4.5] color (Meidt et al. 2014). For the SHA part of the sample, measurements are not available in Querejeta et al. (2015), which is based on the SINGS survey that does not include these objects. This is another reason why such analysis could not be consistently applied in our study. Nevertheless, we present some conclusions based on objects processed in Querejeta et al. (2015). For 9 galaxies in our sample, it was possible to measure the [3.6]-[4.5] color by Querejeta et al. (2015). The contribution of dust radiation to the total flux for these objects ranges from 9% to as much as 40%, averaging around 25%. When accounting for the influence of dust where applicable, we obtain an increase in the average $M/L^{3.6}$ ratio to 0.42. This value is closer to literature values ranging from 0.50 to 0.60 (McGaugh and Schombert, 2015; Meidt et al. 2014, respectively). This correction did not reduce the range of $M/L^{3.6}$, on the contrary, it did not apply to the galaxies that otherwise had a very low mass-to-light ratio. The scaling relationship between dynamic mass and this corrected brightness has larger deviations than the original relationship, which we discuss in the thesis.

It is essential to note that, when we attribute part of the light to emission from dust, increase of M/L ratio in free dynamic models does not change the baryonic mass or the mass distribution of other components, except for the M/L ratio itself. As expected, the fit would converge to the same solution for any constant M/L ratio obtained for evenly and radially symmetrically distributed dust along the disk. On the other hand, in the case of SPS dynamic models, such correction could make a difference in estimating stellar and baryonic masses. Also, in both cases, the contribution of dust mass to baryonic mass could be estimated.

4. SUMMARY

From the mass of individual components for a specific dynamic model for all galaxies (successfully described by the given model), it was possible to construct mass functions, i.e. the proportions of galaxies within a given range of masses in a sample. Ideally the sample is complete within a certain space and represents the distribution of matter in that part of space. In our case, this condition is not fulfilled because objects were selected based on the presence of HI gas, and the space covered by the sample is small. Nevertheless, we consider that within the class of galaxies with a gas disk, completeness in the parameter space is satisfied — the sample covers a very wide range in terms of morphology, gas quantity, dynamics, and mass. Furthermore, the distribution functions obtained in this way indicate possible specificities of our immediate environment and epoch. In that sense, the thesis offers promising results regarding the Milky Way and its typicality, and it is also the subject of work underway.

The obtained distributions of the $M/L^{3.6}$ ratios for the disk in all dynamic models did not exhibit any clustering based on morphology (e.g. irregular vs. spiral). Additionally, there was no discernible regularity in the change of dynamical mass with the variation of the M/L ratio. However, the dynamical mass scales as expected with baryonic (and stellar) mass, with noticeable deviations in galaxies with $M/L > 0.40$.

Correcting for dust does not change the overall amount of component's masses or their relationship for free models, but it does for SPS models since it raises overall M/L.

Such detailed modeling with data of almost unprecedented quality can still be a powerful tool in gaining more insight in universal M/L value or, at least, applicable for certain types of galaxies. From there we can possibly learn about relations between masses of different components, uncover scaling relations and much more.

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References

de Blok, W. J. G., Walter, F., Brinks, E., Trachternach, C., Oh, S.-H., Kennicutt, Jr., R. C.: 2008, *The Astronomical Journal*, **136**, 2648.

Jimenez, R., Verde, L., Treu, T., Stern, D.: 2003, *The Astrophysical Journal*, **593**, 622.

Jovanović, M.: 2017, *Monthly Notices of the Royal Astronomical Society*, **469(3)**, 3564.

Jovanović, M, Samurović, S., Ćirković, M. M., Vudragović, A.: 2021, *Publications of the Astronomical Observatory of Belgrade*, **100**, 247.

McGaugh, S. S., Schombert, J. M.: 2015, *The Astrophysical Journal*, **802(1)**, 18.

Meidt, S. E., Schinnerer, E., van de Ven, G. et al.: 2014, *The Astrophysical Journal*, **788**, 144.

Navarro, J. F., Frenk, C. S., White, S. D. M.: 1997, *The Astrophysical Journal*, **490**, 493.

Papastergis, E., Cattaneo, A., Huang, S., Giovanelli, R., Haynes, M. P.: 2012, *The Astrophysical Journal*, **759**, 138.

Querejeta, M., Meidt, S. E., Schinnerer et al.: 2015, *The Astrophysical Journal Supplement Series*, **219**, 5

Samurović, S., Vudragović, A., Jovanović, M.: 2015, *Monthly Notices of the Royal Astronomical Society*, **451**, 4073.

Walter, F., Brinks, E., de Blok, W. J. G., Bigiel, F., Kennicutt, Jr., R. C., Thornley, M. D., Leroy, A.: 2008, *The Astronomical Journal*, **136**, 2563.