*Dwarf Galaxies: From the Deep Universe to the Present*
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# Mass Distribution in Stellar Structures of Local Dwarfs

**Karín Menéndez-Delmestre**[1], **Yasmin Coelho**[1], **Marco Grossi**[1]
**and Kartik Sheth**[2]

[1]Valongo Observatory, Federal University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil
email: `kmd@astro.ufrj.br`

[2]NASA Headquarters Washington DC, USA

**Abstract.** We study the distribution of mid-infrared light in stellar structures in a large sample ($\sim 400$) of low-mass ($M_{stellar} < 10^9$ $M_{Sun}$) galaxies. Our sample is selected from the Spitzer Survey of Stellar Structures in Galaxies (S4G), which entails deep imaging of nearby galaxies with the IRAC instrument at 3.6/4.5 $\mu$m. Based on the 2D decomposition of the 3.6$\mu$m images, we find that the majority (~65%) of galaxies in our sample is well-fit by a single disk profile. The rest of the sample is more adequately fit by a disk and an additional component (e.g., bar, nucleus, bulge, second disk component). Bars are present in ~11% of the sample, marking a sharp drop in the bar fraction compared to that found for more massive galaxies. The typical contribution of bars to the 3.6 $\mu$m light in dwarfs is ~1-2%, lower than that found in more massive galaxies. These results bring a number of issues into question: why do low-mass galaxies have such low bar fraction? does the bar instability act differently in low-mass galaxies such that a smaller proportion of stellar mass is typically involved in the bar structure? Is the fact that dwarfs are more dark matter dominated playing a role?

**Keywords.** galaxies: dwarf, galaxies: structure, infrared: galaxies

## 1. Introduction

Galaxies in the local universe are a fossil record of events in the distant universe and present critical constraints for examining models of formation and evolution of galaxies. Based on the Spitzer Survey of Stellar Structure in Galaxies (S4G; Sheth *et al.* 2010) database, we have set out to quantify the relative amount of stellar light typically contained within different stellar structures (such as bulge, disk, bar) in nearby galaxies, in the interest of establishing a systematic characterization of the stellar mass distribution in these structures. S4G entails deep mid-infrared (mid-IR) imaging of ~2300 nearby ($< 40$ Mpc) relatively-large ($D_{25} > 1'$) relatively-bright ($m_{Bcorr} < 15.5$) galaxies with the Infrared Array Camera (IRAC) onboard Spitzer at 3.6/4.5 $\mu$m. With a surface brightness limit at 3.6$\mu$m of 27 mag/arcsec$^2$, this survey is unique in its capability to probe stellar surface densities down to $\ll 1$ $M_{Sun}/pc^2$, which is of particular interest when studying faint extended objects. The choice of mid-IR is particularly important because the emission of low mass stars, that dominate stellar mass in galaxies, dominates the flux in these bands. The S4G collaboration makes the reduced images publicly available (Muñoz-Mateos, J.-C. *et al.* 2015) via the NASA/IPAC Infrared Science Archive (IRSA).

In an interest to focus our study on dwarf galaxies, we select all galaxies from the S4G sample with low stellar masses ($M_{stellar} < 10^9$ $M_{Sun}$). Considering that one of our drivers is to explore the prevalence of bars in such galaxies, we restrict our sample to galaxies with inclinations lower than 65 degrees; bars in more inclined galaxies are notoriously difficult to detect. These cuts resulted in a total of 454 dwarf galaxies. As we include into our selection criteria the need for a high-quality decomposition (following the Q = 5 criterium established by Salo, H. *et al.* 2015), our resulting sample contained 338 galaxies.

## 2. Analysis and Main Results

The S4G collaboration undertook the systematic 2D decomposition of $3.6\mu$m images for each galaxy in the S4G sample (see Salo, H. *et al.* 2015) based on the GALFIT decomposition software (Peng *et al.* 2010). As discussed in Salo, H. *et al.* (2015), a number of decomposition approaches were adopted, including an automatic 1-component Sérsic fits, a 2-component Sérsic bulge + exponential disk fits, and a human-supervised multi-component decomposition. We base our analysis on the latter, done by fitting a maximum of 4 components, including (when deemed appropriate by the authors), a central point source, bulge, disk, and bar components. All the results are available via the IRSA database.

Based on the 1-to-4 component 2D decomposition, we find that most of the dwarf galaxies in our sample ($\sim$65%) are well-fit by a single disk profile (i.e., exponential fit). For the remaining 35% of the sample (with two exceptions), the decomposition includes either a single additional component (e.g., bar, nucleus, bulge, second disk component) or in a few cases (8/338) two additional components (e.g., bar + nucleus, bulge + bar). Within the sample, 11% present bars, 10% present nuclei and 10% present secondary disks. We note that what we refer to as a "nucleus" represents the contribution of an unresolved central component, fit with a PSF-convolved point source (see Salo, H. *et al.* 2015). Within the wider context of S4G galaxies it is associated with the emission from an active galactic nucleus (AGN) or a central starburst, however, within our dwarf galaxy sample we attribute it to compact regions of dust likely heated by young stellar clusters.

The two exceptions where disk components were not found to be present correspond to two dwarf galaxies each with a single Sérsic (non-exponential or bulge) component, suggesting an early-type dwarf nature. It is interesting to note that, aside from these exceptions, our sample has a very small contribution from bulges: less than 2% of our sample includes a non-exponential Sérsic (or bulge) component, based on the 2D decompositions. We attribute this result to our sample being mostly composed of late-type dwarfs, based on gas content, location within the main sequence of star-forming galaxies and n-values of the Sérsic index for the single component decomposition.

Our main objective is to quantify the relative stellar mass content in the different individual stellar structures. Beyond identifying the presence of structures in our sample, the main step to achieve this is to quantify the relative stellar light contained in each structure. For this we rely on the $3.6\mu$m light that each individual component contributes to the total model light, available for all S4G galaxy decompositions in Salo, H. *et al.* (2015). We note that by quantifying the individual contribution of each component in this manner we are assuming that residuals are insignificant, which is not always the case (see Figure 1). We are currently in the process of improving on this approach.

We find that, although bars appear to display a variation in prominence, their typical contribution to the 3.6 $\mu$m light in dwarf galaxies is $\sim$1-2%. The nuclei identified in our sample do not contribute more that 5% to the model light, with one exception where the galaxy is associated with a 20% contribution from a central point source. We discuss further the bar results in the next section and relay a more in-depth discussion of the contribution of the remaining stellar structures to Menéndez-Delmestre *et al.*(in prep).

## 3. Discusssion and Future Perspectives

Starting with de Vaucouleurs seminal work on the morphological classification of bright galaxies based on optical imaging (de Vaucouleurs, G. 1963), a number of studies have

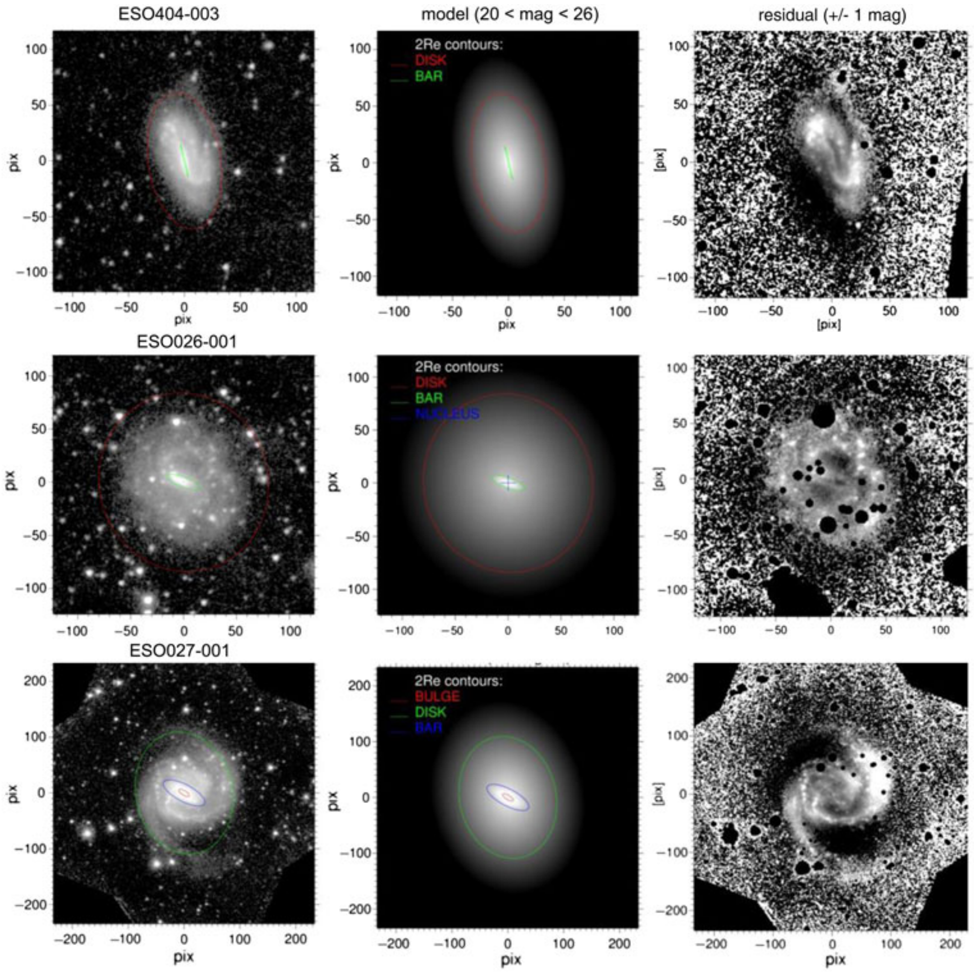

**Figure 1.** Example of the decomposition for 3 dwarf galaxies in our sample: (left) 3.6$\mu$m image, (center) model, (right) residual using GALFIT (for details on decomposition, see Salo, H. *et al.* 2015). Although for the moment our analysis has focused on the main stellar structures represented in the model (i.e., disk, bar, bulge, nucleus), this figure clearly shows how spiral arms and other not-so-regular structures may contribute to the stellar light as traced by the 3.6$\mu$m-band. Our project will expand in time to study these structures and their contribution to the stellar mass budget of dwarf galaxies.

demonstrated that bars are ubiquitous in massive galaxies, with the optical bar fraction of $\sim 2/3$ being preserved as we extend the analysis to the near-IR (e.g., Eskridge, P., *et al.* 2000; Menéndez-Delmestre *et al.* 2007) and, more recently, out to the mid-IR (Erwin, P. 2018). Of particular interest is that Erwin, P. (2018), by identifying bars in galaxies based on the visual inspection reported by Herrera-Endoqui M., Díaz-García S., Laurikainen E., Salo H. (2015) and Buta R. J., *et al.* (2015), identified a sharp drop for low-mass ($M_{stellar} < 10^9\ M_{Sun}$) galaxies. The results of our present study confirm this trend using a distinct methodology (i.e., 2D decomposition).

Considering that a disk is expected to succumb to the bar instability within a few Gyrs (e.g., Athanassoula *et al.* 2002) the question arises as to why many disk galaxies remain unbarred, be it a dwarf or a more massive galaxy. Over the years we have learned much about this based on simulations. For instance, the formation of a bar can be delayed

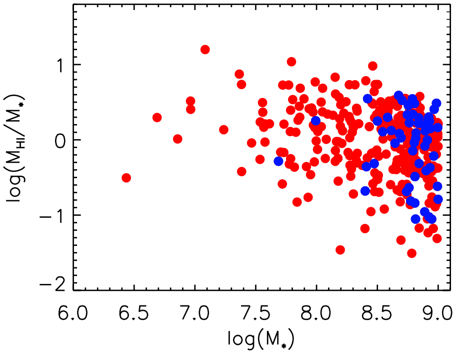

**Figure 2.** We find that 11% of the dwarf galaxies in our sample present a bar. This is consistent with studies that show a steep decrease in the bar fraction for low-mass galaxies. The reason for this drop in bar fraction is still unclear, as a disk will naturally form a bar, unless it is particularly gas rich, dynamically hot, or has a dominant dark matter halo. The figure shows HI content as a function of stellar mass in our sample for barred (blue points) and unbarred (red points) galaxies. Bars in our sample are not found in galaxies with less gas; they seem to be present independently of gas richness. They are, however, very clearly biased towards the more massive systems.

significantly by an initially dominant dark matter (DM) halo and a high gas fraction (Athanassoula & Sellwood 1986; Athanassoula *et al.* 2013); it can also be inhibited in dispersion-dominated disks (Athanassoula & Sellwood 1986) as observationally shown in Sheth *et al.* (2012) for dynamically-hot galaxies, where $\sigma/V_{rot} > 1$. Within this context, we consider the general characteristics of our dwarf sample: they are generally more DM dominated than the general population of galaxies; they are preferentially late-type dwarfs (based on a 2D decomposition that reveals a dominant disk component in ~99.5% of our sample); they present a wide variation in gas-richness as measured by the HI mass fraction (see Figure 2); and they host star formation activity that places them within the main-sequence of star-forming galaxies. Figure 2 shows two important details regarding our general result of a low bar fraction for our sample: (1) bars are preferentially found in the massive end of our sample (reproducing the expected trend also shown by Erwin, P. 2018) and (2) they do not appear to be selective as to how gas rich the host galaxy is. This suggests that, although dwarf galaxies are typically associated with high gas fractions, the lack of bars may not be uniquely and/or directly associated to this property. The question of why the majority of low-mass galaxies do not host bars still remains an open question. A more in-depth investigation of internal dynamics and the role of the DM halo is required to help us understand the drop in bar fraction for low mass galaxies.

The investigation of the bar fraction as a function of redshift provides a broader context to these results. Sheth *et al.* (2008) showed that the most massive galaxies formed their bars first, with their bar fraction being established already at $z \sim 0.8$. Meanwhile the bar fraction for the low-mass/bluer galaxies drops beyond $z \sim 0.3$, suggesting that bars in these systems form later. The low fraction we measure for low-mass galaxies is thus consistent with the trend of low mass galaxies still in the process of forming their bars.

Turning to how much stellar light (as portrayed by 3.6$\mu$m images) is contained in bars, we report a very small contribution ($\sim 1-2\%$) in dwarf galaxies. We note that we have undertaken a separate, preliminary study of stellar structures in a small sample (~40) of barred S4G galaxies (i.e., with a bar component in their 2D decomposition) very similar to the one presented here for dwarf galaxies. We find that bars in more massive galaxies comprise typically 4% of the total (model) stellar light, but that significant variation exists, with the bar component contributing more than 10% of the mid-IR light in 20%

of the cases. This leads us to conclude that bars in dwarfs, with a maximum of 2% contribution to the mid-IR light, contribute significantly less than those in more massive barred galaxies. This suggests that in low-mass disks, a smaller portion of the total stellar mass is involved in the bar instability. Why is the bar instability acting differently in low-mass disks? Is the fact that dwarfs are more DM dominated playing a role? At this time, many of these questions remain open. Further analysis and integration with simulations may allow us to, in the near future, shed some light in these intriguing findings.

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## Discussion

KMD: Have you looked for spiral arms in your sample, and do they correlate with bars?

A: Not yet, but it is something that we plan to do by looking at the GALFIT residuals.