How Spiral Structure Depends on Baryonic Mass Fraction of Galaxies

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Abstract

In this study, we investigate spiral structures in galaxies. We use Galaxy Zoo (GZ) analysis of Dark Energy Spectroscopic Instrument (DESI) survey imaging to select a sample of 3533 spiral galaxies, allowing us to gather their morphological properties, including presence of spiral arms and arm number. Our analysis incorporates data from the Arecibo Legacy Fast ALFA (ALFALFA) survey, specifically utilizing this HI data to estimate the baryonic mass, and calculate the dynamical mass fraction of HI detected galaxies. Our findings demonstrate a positive correlation between the likelihood of presence of well-defined spiral arms galaxies and their baryonic mass fraction. We also observe a relationship between spiral arm number and the baryonic mass fraction. These observations can help improve understanding of how spirals form in galaxies with the affect of dark matter.

Introduction

A spiral arm is a long, curved region which extends outward from the center of many disk galaxies. This region is filled with a higher density of stars, gas and dust compared to the inter-arm regions, indicating spirals play an important role regulating star formation in galaxies. These conspicuous spiral features are instrumental in the classification of disk galaxies as members of the spiral galaxy category. Spiral galaxies can be further classify into arm classes such as "grand design" or "flocculent." A grand design pattern is defined as spiral arms that are highly symmetric and continuous and exists more often in two-arm galaxies (Sellwood & Masters 2022), while flocculent spirals are more patchy, and often "many"-armed. Most formation models include some kind of density wave, indicating that spiral arms are wave-like patterns that move through the galactic disk (Sellwood & Masters 2022). It is noteworthy that the presence of dark matter halos shape gravitational potential within galaxies, meriting consideration as a factor in shaping the observed spiral architecture (Hart et al. 2018).

The prevalence of spiral structure among galaxies at low red-shifts is an established phenomenon (Hart et al. 2018). We quantitatively assess the extent of the spiral structure exhibited by galaxies in this study. Prior investigations have illuminated the stabilizing influence of dark matter on galactic structures. Specifically, self-excited instabilities within the disk, more likely in high baryon fraction galaxies, have been attributed to the formation of spiral structures (Sellwood & Masters 2022). Additionally, the number of galaxy arms is a feature of the spiral galaxy pattern which is also impacted by baryonic mass fraction. For example, research by Sellwood & Carlberg (1984); Athanassoula et al. (1987); Hart et al. (2018) indicates that spiral patterns subject to swing amplification tend to exhibit a greater number of arms in galaxies characterized by lower disk mass (or baryonic) fractions.

In this paper, we conduct an investigation by using visual classification from Galaxy Zoo DESI and HI emission line profile of Arecibo Legacy Fast ALFA (ALFALFA, Haynes et al. 2018) to explore the correlation between properties of the patterns of spiral arms and baryonic mass fraction of galaxies in a larger sample (GZ DESI, Walsmsley et al. in press). Our aim is to elucidate the intricate relationships between spiral arm properties and the baryonic mass fraction across a diverse galaxy sample. Specifically, we focus on the propensity of galaxies to exhibit high probability spiral patterns and the quantification of their arm counts. By delving into these aspects, we seek to enhance our understanding of the intricate connections between spiral structures and galaxy properties.

Data and Sample Selection

We investigate the galaxy morphology dataset curated by Galaxy Zoo DESI (GZ DESI, Walsmsley et al. in press). Galaxy Zoo (GZ) involves citizen scientists examining galaxy images to gather morphology data. GZ DESI utilizes volunteers' classifications to assess galaxy shapes in the DESI samples (GZ DESI, Walsmsley et al. in press). Citizen scientists review galaxy images and make choices from provided options to classify them. Galaxy morphology data is expressed as probabilities indicating the fraction of citizen scientists who observed specific features in each galaxy.

We also integrate essential parameters such as HI mass and dynamic mass, derived from the HI emission line profile of galaxies sourced from the ALFALFA database (Haynes et al. 2018). The crucial attributes of HI mass, stellar mass (based on optical data) and rotational width are drawn from the ALFALFA-SDSS Galaxy Catalog (Yu et al. 2022), a resource that is limited to galaxies rich in gas content, hence characterized by HI detection.

Our sample construction involves the deliberate exclusion of edge-on galaxies, achieved by limiting the sample to galaxies with axial ratio $b/a > 0.4$ in conjunction with $p_{\rm features} > 0.430$. This results in 7901 featured or disk galaxies with potentially visible spiral arms. To circumvent potential signal contamination arising from radar interference at the San Juan airport, we restrict our sample by imposing constraints of $\log M_{\rm star} > 9.4$ and $z < 0.05$ (Haynes et al. 2018).

Method

We calculate the total baryonic mass by adding up the gaseous mass and stellar mass of the galaxies. We estimate the baryonic mass ($M_{\rm bary}$) using the relation $M_{\rm bary} = 1.07 M_* + \frac{4}{3} M_{HI}$, which (as explained by Goddy et al. 2023) accounts for both cosmic He ($M_{\rm gas} = \frac{4}{3} \times M_{HI}$ considering the universe's hydrogen composition of approximately 75% by mass) and the contribution of molecular hydrogen. Baryonic mass fraction is obtained by dividing the baryonic mass by the total, or dynamic mass. The total mass of galaxies ($M_{\rm dyn}$) is approximated through the dynamic mass derived from the HI emission line profile with the relation $M_{\rm dyn} = \frac{R_{HI} V_{\rm rot}^2}{G}$, where R_{HI} is the radius of the HI disk and the $V_{\rm rot}$ means the physical rotation speed of the HI disk.

Observations reveal a most of our galaxies have baryonic mass fractions in the range of 0.05–0.4 (see right panel of Figure 1). In order to enhance the statistical robustness of our investigation, this paper narrows focus to this specific range.

Within the context of GZ DESI, we select spiral galaxies with a probability ($p_{\rm spiral}$) threshold exceeding 0.5 (GZ DESI, Walsmsley et al. in press). High probability spiral galaxies are identified with a stricter criterion of $p_{\rm spiral} > 0.8$. The probability of spiral structures in galaxies indicates the likelihood of a disk galaxy being classified as a spiral galaxy through visual inspection. High spiral probability galaxies exhibit clearer and more prominent spiral structures compared to other spiral galaxies. The spiral fraction is the ratio between the number of high spiral probability galaxies and the total number of spiral galaxies within a designated sample.

We classify the 3533 spiral galaxies by their arm numbers with GZ DESI. A galaxy is categorized as a one-arm galaxy if the probability parameter for having a single arm exceeds 0.3 and all corresponding parameters for alternative galaxy types fall below 0.2. This classification methodology yields the count of galaxies for each arm number, as presented in Table 1. Notice that some spirals are not classified in this method. Among those galaxies, we consider 2− arms and 4−armed galaxies as grand-design spiral galaxies, since they are symmetric.

Table 1: Number of spirals with clearly classified different Arm Numbers

Galaxy phase	Number of galaxies
1 arm	9
2 arms	842
3 arms	7
4 arms	18
More than 4 arms	23
Cannot tell	1331

Results

We studied the correlation between the spiral feature of disk galaxies and their baryonic mass fraction. We notice a trend that a higher baryonic mass fraction spiral galaxies consistently corresponds to an increased likelihood of them being classified as a high probability spiral, as the left panel of Figure 1 shows.

We also consider the classification of the number of spiral arms. Among all the nearby galaxy samples, the majority of the galaxies are classified as “2- and 4-arm” galaxies and “cannot tell” galaxies. We group 2-armed and 4-armed galaxies together into a single category. This is because they both display distinct symmetric spiral arms. This is the primary reason we label them as ”grand design galaxies.” On the contrary, the “cannot tell” galaxies are a class of disk galaxies that are without clear symmetrical spiral arms, and may be associated with flocculent spirals.

Figure 2 shows the distributions and trends for galaxies with different arm numbers on the baryonic mass fraction. For the distribution in Figure 2(a), we notice that galaxies with more than four arms tend to be found in galaxies characterized by a higher baryonic mass fraction. In comparison, spiral galaxies with two and four arms tend to possess a slightly lower baryonic mass fraction. Subsequently, spiral galaxies with three arms are observed to possess the lowest baryonic mass fraction, followed by those with one arm.

This correlation of spiral likelihood and baryonic mass fraction of disk galaxies becomes interesting when considering the specific arm structures within spiral galaxies, especially for the “grand design” galaxies (galaxies with 2- and 4- arms) compared to ”flocculent” (“cannot tell” in GZ) as

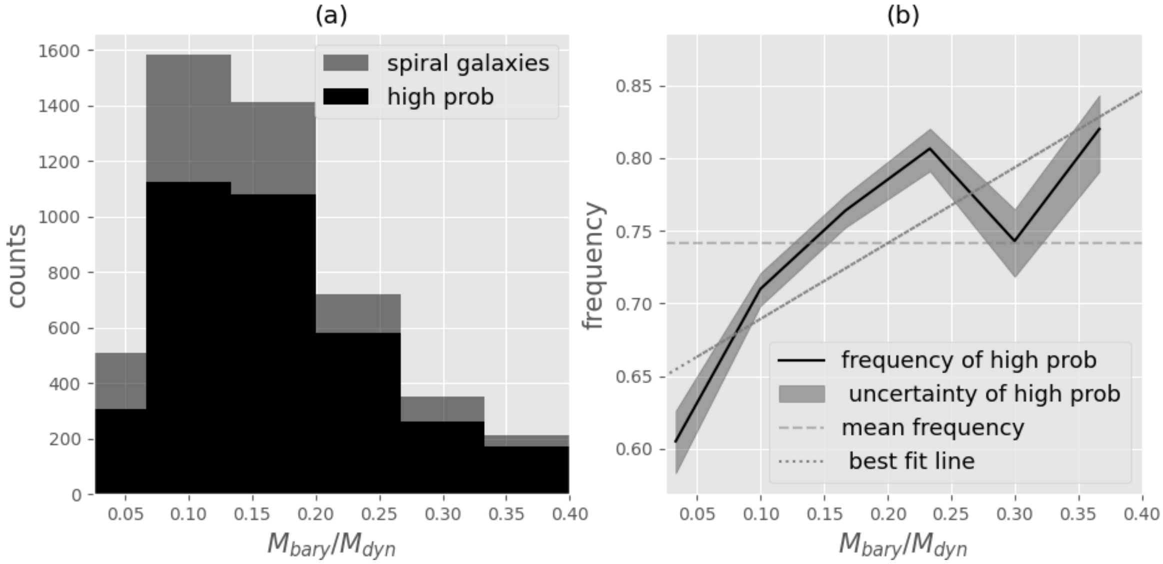

Fig. 1.— The two diagrams depict the distribution of spiral galaxies based on their probabilities of being spiral ($p_{\rm spiral} > 0.5$) and those with even higher probabilities ($p_{\rm spiral} > 0.8$). The frequency is a fraction whose numerator is the quantity of high probability spiral galaxies in each bin, and its denominator is the quantity of all the spiral galaxies in each bin. We concentrate on galaxies with baryonic mass fraction in range of 0.05–0.4, since most spiral galaxies have a baryonic mass fraction in this range. Figure 1(a) presents the galaxy count in different baryonic mass fraction of galaxies bins. Figure 1(b) is a frequency histogram shows the likelihood for a spiral galaxies being classified as a high probability spiral galaxies across different baryonic mass fraction bins

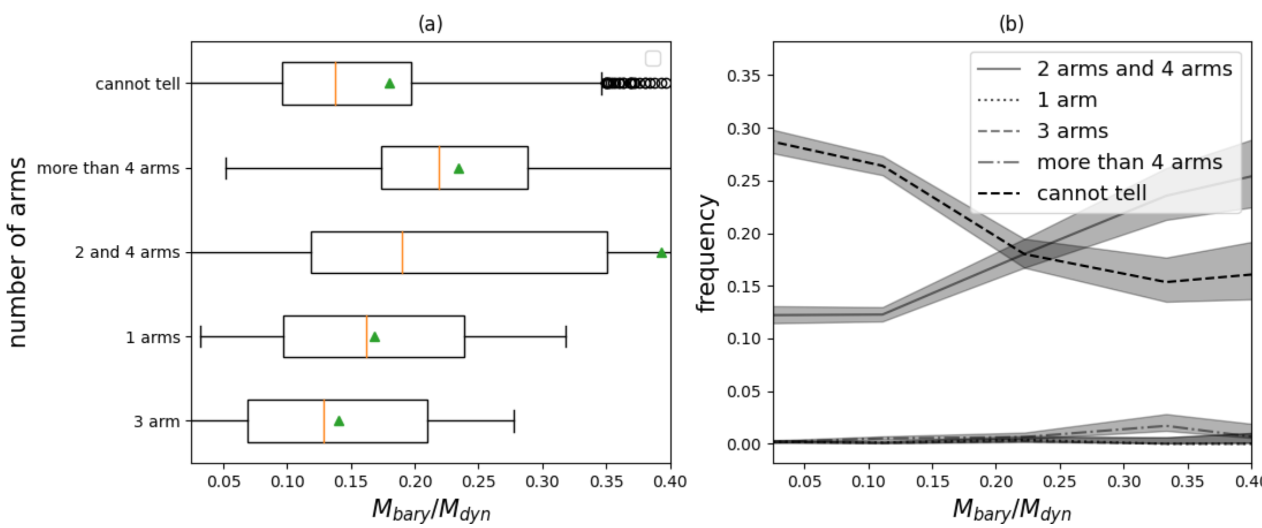

Fig. 2.— The two figures depict the distribution of spiral galaxies ($p_{\rm spiral} > 0.5$) with various arm numbers on baryonic mass fraction of galaxies. Figure (a) is a box plot illustrating the typical baryonic mass fractions of spiral galaxies with different arm numbers in our sample.The light color line in the middle of the box is the median, the triangle means the mean value. Figure (b) shows the fraction of spirals with clearly identified (i.e. high vote fraction) specific arm numbers (as labelled) as a function of baryonic mass fraction.

Figure 2(b) shows. “Grand design” spirals are more likely to be found at high baryonic fraction. Conversely, the “cannot tell” galaxies shows an opposite trend. We observed a decrease in the “cannot tell” galaxies when observing high baryonic mass fraction galaxies. Among the other types of spiral galaxies the total counts are much smaller, however ”more than 4-arms” galaxies are more common in galaxies with a higher baryonic mass fraction while 3-arm galaxies and 1 arm galaxies are almost evenly spread over different baryonic mass fractions, but show a slight decrease on the high baryonic mass fraction.

Summary and Conclusion

We observed a positive correlation between the baryonic mass fraction and the spiral feature in general. Additionally, distinct patterns and variations in the baryonic mass fraction have been identified among spiral galaxies with differing arm numbers. The underlying mechanism for the relationship remains elusive. Further examination is necessary, including the assessment of potential observational biases. Our study offers a potential foundation for future research aimed at further understanding of spiral structure within disk galaxies.

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