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Galaxy Zoo: are we observing an epoch of bar formation in massive disk galaxies?

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Abstract. We combine photometric and spectroscopic data from from Cosmic Evolution Survey (COSMOS) with visual galaxy classifications from Galaxy Zoo: Hubble (GZH) to produce a volume ($0.4 \le z \le 1.0$) and mass limited ($9.7 \le \log(M_{sun}/M_{star}) \le 11.$) sample of 2,623 disk galaxies, with 330 of these identified as hosting a barred structure. We find that the fraction of bars found in disk galaxies decreases towards higher redshifts, confirming the redshift evolution trend seen by Sheth et al. (2008). We extend this trend to higher redshifts than previously seen (from $z \approx 0.84$ to $z=1.0$) for such a sample size, finding that the bar fraction decreases across the timescales we explore; from $f_{bar} \approx 0.22$ at $t_{lookback} \approx 4.2$Gyrs ($z \approx 0.4$) to $f_{bar} \approx 0.06$ at $t_{lookback} \approx 7.8$Gyrs ($z \approx 1.0$). To explore whether this evolution depends on stellar mass, we split our disk sample into three stellar mass bins ($9.7 \le \log(M_{sun}/M_{star}) < 10.2$; $10.2 \le \log(M_{sun}/M_{star}) < 10.7$ and $10.7 \le \log(M_{sun}/M_{star}) \le 11.0$). We find that the redshift evolution of the bar fraction is driven by the more massive galaxies, while the bar fraction of low mass galaxies remains constant across the whole epoch explored. We extend our results to include a low redshift sample of disk galaxies (Masters et al. 2012), which shows that the higher bar fraction in the local universe is also due to the more massive galaxies, while the low mass galaxies exhibit a similar bar fraction as seen in our high redshift sample of galaxies. We suggest that the more massive galaxies become disk dominated and dynamically cool sooner than lower mass galaxies, thus allowing them to form and sustain a barred structure. We also suggest that disk galaxies are reaching a point where they are less dominated by violent galaxy-galaxy interactions, and that secular processes begin to dominate their evolution, and so this produces and epoch of bar formation in the most massive galaxies at z=0.8- 1.

Key words. galaxies: spiral – galaxies: evolution – galaxies: structure

1. Introduction

The abundance of bars in our local universe has been explored extensively, with the fraction of disk galaxies hosting barred structures ranging from $f_{bar} \approx 0.3$ (Masters et al. 2011; Nair & Abraham 2010) to $f_{bar} \approx 0.5$ (Barazza et al. 2008; Aguerri et al. 2009), and even as high as $f_{bar} \approx 0.7$ when observed in the near-infrared bands (Eskridge et al. 2000; Menéndez-Delmestre et al. 2007). Simulations have also shown the importance of bars in the evolution of a disk galaxy, with bar formation

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and growth being one of the most important processes in the secular evolution stage of a disk galaxies life (see Kormendy & Kennicutt 2004; Combes 2009; Coelho & Gadotti 2011 for examples).

Observations exploring the abundance of bars at higher redshifts are less extensive due to the difficulty of instruments being able to resolve the internal structure of galaxies. Only *Hubble Space Telescope* (*HST*) images have provided catalogues where such observations are possible. Identifying the abundance of bars at higher redshifts requires us to explore the redshift evolution of the bar fraction over these wide timescales. Initial research offered contrasting results, with several papers (see Elmegreen et al. 2004; Jogee et al. 2004; Sheth et al. 2004) showing no evolution of the bar fraction up to $z \approx 1$. However, Abraham et al. (1999) and Sheth et al. (2008) (whose disk galaxy sample was a magnitude larger than any previous samples ≈2,000 galaxies) both saw a decreasing bar fraction towards higher redshifts.

Understanding whether the bar fraction evolves over cosmic time is important. As bars can only form in galaxies which have become relaxed, cool and disk dominated; the presence of a barred structure tells us that the host galaxy is in a dynamically relaxed state. Once a disk dominated galaxy reaches this epoch, secular processes begin to dominate its evolution, leading to the formation of other sub-structures (such as bars, bulges, warps, rings). With the limited observations available providing contrasting results, it is clear that more work is required to determine whether the trend seen by Sheth et al. (2008) is true, or whether the earlier observations were correct in their assertion that the bar fraction remains constant.

2. Sample selection

We combine photometric and spectroscopic data from the Cosmic Evolution Survey (COSMOS) (Scoville et al. 2007) to produce a volume ($0.4 \leq z \leq 1.0$) and stellar mass limited ($9.7 \leq \log(M_{sun}/M_{star}) \leq 11.0$) catalogue of *HST* imaged galaxies. We combine this catalogue with visual morphological classifications made by volunteers using the third incarnation of the citizen science Galaxy Zoo programme (www.galaxyzoo.org, Lintott et al. (2008, 2011); Galaxy Zoo: Hubble (GZH). We apply stringent cuts to the weighted expected likelihoods calculated for each morphological feature, to produce a final sample of 2,623 disk galaxies (hereafter GZH sample), with 330 identified as hosting a barred structure. See Melvin et al. (in prep.) for furthur details.

The careful selection criteria applied to produce the GZH sample alleviates several biases that may affect a volunteers ability to identify bars, especially in galaxies found towards the higher redshift end of our sample. Such biases we have attempted to eliminate include the effects of surface brightness dimming and maximising a volunteers ability to identify bars in the smaller disk galaxies. We also apply an inclination cut of $\log(a/b) > 0.3$, ensuring that only face-on disk galaxies are included in the final GZH sample.

The selection criteria also allows us to combine our GZH sample with a low redshift sample (see Masters et al. 2011 and Masters et al. 2012 for further details).

3. Summary of results

The redshift evolution of our GZH sample is shown in Figure 1 (taken from Melvin et al. in prep.). Overall, we find that the fraction of bars found in disk galaxies decreases across the redshift range we explore. The data is split into 0.3Gyrs bins, with the bar fraction then calculated for each bin. The number of barred disk galaxies and disk galaxies are shown as a fraction by each data point. We also show the 1σ error for each point, with the grey tracks identifying this error through the whole trend. To aid the readers eye, we also include a linear fit to our data points (bold line), as well as showing the mean bar fraction for the whole sample (dot-dashed line), $\overline{f_{bar}}=0.125$.

Overall, our results show that the bar fraction decreases across the timescale we explore, from $f_{bar}=0.22$ at $t_{lookback} \approx 4.2$Gyrs ($z \approx 0.4$) to $f_{bar}=0.06$ at $t_{lookback} \approx 7.8$Gyrs ($z \approx 1.0$). This redshift evolution is consistent with that observed by Sheth et al. (2008), with our obser-

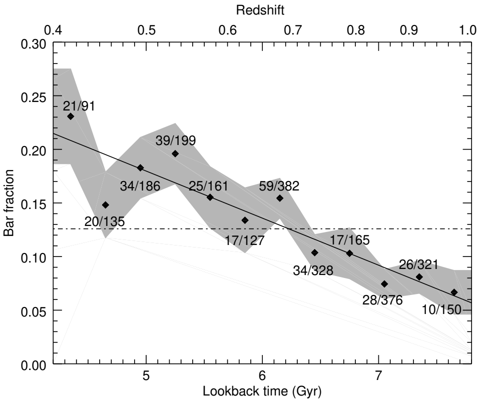

Fig. 1. Redshift evolution of the bar fraction for our GZH sample. Data is split into δ0.3Gyr bins, with the bar fraction calculated for each bin. The number of barred disk galaxies and disk galaxies is shown as a fraction above each data point. Grey track lines show the 1σ error for each point. We show a linear correlation of our data points (bold line) to guide the readers eye, as well as showing the median bar fraction of the whole sample (dot-dashed line).

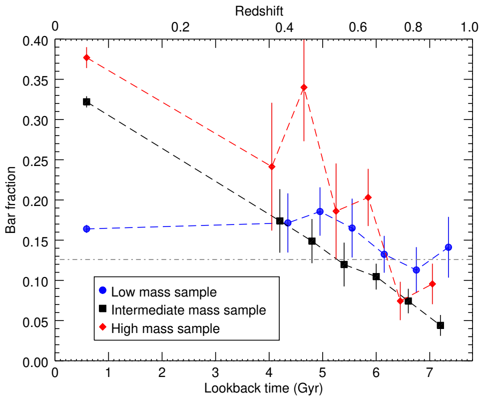

Fig. 2. Redshift evolution of the bar fraction for three mass bins. These bins are defined as low mass: $9.7 \leq \log(M_{sun}/M_{star}) < 10.2$ (blue); intermediate mass: $10.2 \leq \log(M_{sun}/M_{star}) < 10.7$ (black) and high mass: $10.7 \leq \log(M_{sun}/M_{star}) \leq 11.0$ (red). We extend our GZH sample to include our low redshift sample (from Masters et al. 2012, showing that the evolution of the bar fraction is driven by the most massive galaxies.

vations extending their initial results to higher redshifts (see Melvin et al. in prep. for an in depth comparison).

We also split our GZH sample into three mass bins ($9.7 \leq \log(M_{sun}/M_{star}) < 10.2$, $10.2 \leq \log(M_{sun}/M_{star}) < 10.7$ and $10.7 \leq \log(M_{sun}/M_{star}) \leq 11.0$) to determine whether the redshift evolution of the bar fraction is dependant on mass. Figure 2 (taken from Melvin et al. in prep.) shows that both the high mass (red) and intermediate mass (black) samples drive the bar fraction higher., while the low mass sample (blue) remains at a steady level ($f_{bar} \approx 0.15$). These mass bins are also applied to our low redshift sample, and the trends observeed at higher redshifts continue to be seen in the local universe.

Overall, we find that the redshift evolution of the bar fraction is driven by the most massive galaxies. We suggest that this is because more massive galaxies become disk dominated and dynamically cool sooner than lower mass galaxies, and are therefore able to form and sustain barred structures. We also suggest that we observe an epoch of bar formation at $t_{lookback} \approx$6-7.8Gyrs ($z \approx$0.7-1), where the bar fraction roughly doubles for the intermediate mass galaxies and trebles for the high mass galaxies. We propose that this era of bar formation coincides with the evolution of more massive galaxies being dominated by secular processes.

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