Barred Galaxies in the Coma Cluster

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Abstract. We use ACS data from the HST Treasury survey of the Coma cluster (z ∼ 0.02) to study the properties of barred galaxies in the Coma core, the densest environment in the nearby Universe. This study provides a complementary data point for studies of barred galaxies as a function of redshift and environment. From ∼ 470 cluster members brighter than M_I = −11 mag, we select a sample of 46 disk galaxies (S0–Im) based on visual classification. The sample is dominated by S0s for which we find an optical bar fraction of 47 ± 11% through ellipse fitting and visual inspection. Among the bars in the core of the Coma cluster, we do not find any very large (a_bar > 2 kpc) bars. Comparison to other studies reveals that while the optical bar fraction for S0s shows only a modest variation across low-to-intermediate density environments (field to intermediate-density clusters), it can be higher by up to a factor of ∼ 2 in the very high-density environment of the rich Coma cluster core.

1 Introduction

Bars are the most efficient internal driver of secular evolution in disk galaxies. They efficiently redistribute angular momentum in the disk and drive gas to the central regions of galaxies where it can pile up and initiate powerful starbursts.

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In this way, bars are thought to build disky central components known as pseudobulges (Kormendy 1979; Combes et al. 1990; Kormendy 1993).

How does the frequency of barred disk galaxies vary across different environments and what does this imply about the evolution of bars and their host galaxies? Quantitative results addressing this issue are only starting to emerge. Several recent studies (Barazza et al. 2009; Aguerri et al. 2009; Marinova et al. 2009, hereafter M09) find that the optical bar fraction shows at most a modest variation ($\pm 10\%$) between field and intermediate density environments (e.g., groups and moderately rich clusters). However, some studies (Barazza et al. 2009; Thompson 1981; Andersen 1996) have suggested that, within a galaxy cluster, the bar fraction is higher in the dense core regions than the outskirts. This remains an open question due to issues such as limited number statistics in the core and uncertainties in cluster membership.

We explore these questions in Coma, the richest cluster in the nearby Universe. Our results provide a comparison point for studies of barred galaxies in field and group environments in the nearby universe and at high redshift.

2 Data and Cluster Sample

Our data come from the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) Treasury survey of the Coma cluster at $z \sim 0.02$ (Carter et al. 2008). Due to the 2007 failure of ACS, the survey is only $\sim 28\%$ complete. The available data predominantly cover the cluster core and map an area of 274 arcmin$^2$ down to a limiting magnitude of $I = 26.8$ mag in F814W (AB mag). Source extraction yields 472 galaxies with $I \leq 24$ mag ($M_I \sim -11$ mag). Cluster members are picked from the membership catalog of Trentham et al. (in preparation) where galaxies are assigned a membership class $C$ from 0 to 4. Galaxies with $C = 0$ are spectroscopically confirmed members. Galaxies without spectroscopic redshifts are assigned a membership likelihood based on surface brightness and morphology, such that $C = 1$ to 3 represent very likely to plausible members. Out of the 472 galaxies with $I \leq 24$ mag, 470 are considered as cluster members, with the breakdown in classes 0 to 3 being 41%, 7%, 27%, 25%. We use this sample for the rest of the study.

All the 470 galaxies were assigned visual morphological types (Trentham et al. in prep.), which include ellipticals (E), lenticulars (S0), spirals (Sa–Sm), irregulars (Im), and dwarfs. Where available, Hubble types were taken from the Third Reference Catalog of Bright Galaxies (RC3; deVaucouleurs et al. 1991), otherwise galaxies were classified into Hubble types based on a visual estimate of the prominence of the bulge, tightness of the spiral arms, and clumpiness of the disk. The absolute magnitude distribution for the total cluster sample, and the breakdown for different morphologies is shown in Fig 1a. Although we use visual classification without further magnitude cuts to identify dwarfs, it is good to note that the visually identified dwarfs are faint as expected, and have $M_I \geq -17$ mag (Fig. 1a).

As bars are intrinsically a disk phenomenon, it is the norm to characterize the frequency of large-scale or primary bars by citing the fraction $f_{\text{bar-opt}}$ of disk galaxies with bars, where disk galaxies are defined to be systems harboring
a large-scale outer disk. At the bright end, disk galaxies include S0s and Sa to Im, while among dwarf systems, they include dwarf irregulars (dIrr) and potentially some dS0s with disk components. In these proceedings, our goal is to measure $f_{\text{bar-opt}}$ for non-dwarf disk galaxies of Hubble types S0 to Im, while the investigation of bars in dwarf galaxies will be described in a future paper. The first challenge is to identify the disk galaxy sample (S0s to Im). The danger in identifying disks only by color or Sérsic cut in clusters has been discussed extensively by M09, and we therefore use the visual classifications for the Coma sample described above. We select all disk galaxies ranging from S0 to Im, excluding two galaxies that are partially off the edge of a tile and one that is a distorted merger remnant. This brings our final disk sample to 46 galaxies. As illustrated in Fig. 1b, the disk sample is dominated by S0s as expected from the morphology-density relation.

3 Bar Identification

We use ellipse fitting to identify bars and also perform an extra check through visual classification for all galaxies. As described in our earlier work (Jogee et al. 2004; Marinova & Jogee 2007, hereafter MJ07; M09), we perform ellipse fitting and then classify galaxies as inclined, barred, or unbarred, based on the radial profiles of ellipticity ($e$) and position angle (PA), as well as overlays of the fitted ellipses onto the galaxy images. A galaxy is classified as ‘inclined’ if the outer disk inclination $i \geq 60^\circ$. Following common practice, we exclude the 16 inclined galaxies that we find because it is difficult to identify morphological features in highly inclined galaxies. From the remaining sample of moderately inclined disks, we classify a galaxy as barred if (1) the $e$ rises to a global maximum, $e_{\text{bar}} > 0.25$, while the PA remains relatively constant (within $20^\circ$), and (2) the $e$ drops by at least 0.1 and the PA changes at the transition between the bar and disk region. The change in PA between the bar and disk region is statistically expected, as the line of nodes for the bar and disk are oriented independently.

These characteristics work well in lower-density environments (see MJ07), where disk galaxies with extremely large bulge-to-disk ratios are rare. However, in the core of the Coma cluster such galaxies exist, and when the bar is oriented perpendicular to the disk major axis, the ellipticity of the bar isophotes can be diluted by the extremely large bulge. As a result, the above criterion (1) is not satisfied: specifically, the peak bar $e$ in the ellipticity radial profile is not the global maximum, and the PA presents a ‘bump’ at the location of the bar instead of remaining flat. There are three such cases in our sample (marked ‘vis’ in Fig. 1c), and for these we use visual inspection to classify the galaxy as barred. We note that in field and intermediate-density samples, the bar signature may sometimes be masked in the optical by dust and patchy star formation. However, in the dense Coma core, we expect dust extinction to have little effect.

Overall in the sample of moderately inclined disks of type S0–Sm, we find 10 barred and 20 unbarred systems through ellipse fitting and visual classification. Our classifications are summarized in Table 1 and barred galaxies are shown in Fig. 1c.
4 Results and Comparison to Studies Across Different Environments

The optical bar fraction $f_{\text{bar-opt}}$ across the disk sample of S0 to Im galaxies is given by $N_{\text{bar}} / (N_{\text{bar}} + N_{\text{unbar}})$, where $N_{\text{bar}}$ and $N_{\text{unbar}}$ represent the number of barred and unbarred disk galaxies, respectively, in the moderately inclined sample. We find that $f_{\text{bar-opt}}$, averaged across (S0-Im) galaxies, is $10/30$ or $33\pm9\%$ (Table 1).

However, compiling an average bar fraction across a wide range in Hubble types only gives limited insight since recent studies show that the optical bar fraction is a strong function of host galaxy properties, such as the bulge-to-disk ratio ($B/D$) and galaxy luminosity. Specifically, Barazza et al. (2008) and M09 show that the optical bar fraction at $z < 0.03$ is highest in galaxies that are disk-dominated and have very low $B/D$. In addition, in M09 we find in the A901/902 clusters at $z \sim 0.165$ that for a given morphological class, $f_{\text{bar-opt}}$ is higher for brighter galaxies. Unfortunately, the Coma sample is too small to be split into bins of $B/D$, luminosity, and Hubble types. However, it is clear from Table 1 and Fig. 1b that the sample of disks is dominated by S0s and that the optical bar fraction is driven by these galaxies. Therefore, when comparing our results on Coma to other studies, we focus on the optical bar fraction for S0s. We find $f_{\text{bar-opt}}$ for S0s is $47\pm11\%$ (row 2 of Table 1). We consider this value to be an upper limit because it is likely that we are missing some unbarred S0s, which are easily confused with ellipticals.

In Table 2, we show a comparison with: a previous study of the Coma cluster by Thompson (1981, T81) using visual classification to identify bars; M09 for barred disks using ellipse fitting in the Abell 901/902 cluster system at $z \sim 0.165$; bars in Virgo (Giordano et al. 2010, in prep., G10); and Aguerri et al. (2009, A09) who study barred disks using ellipse fitting and Fourier decomposition at $z \sim 0.01–0.04$ in environments ranging from the field to intermediate densities comparable to cluster outskirts.

Table 1. Disk sample classifications based on ellipse fits and visual inspection ($N_{\text{total}} = 46$).

| All          | Highly inclined | Unbarred | Barred | $f_{\text{bar,opt}}$ |
|--------------|-----------------|----------|--------|----------------------|
| S0–Sm 46     | 16              | 20       | 10     | 33±9%                |
| S0 30        | 13              | 9        | 8      | 47±11%               |
| S0–Sab 35    | 14              | 12       | 9      | 43±11%               |
| Sb–Sm 11     | 2               | 8        | 1      | 11±10%               |

Table 2 shows that for the core of the Coma cluster, our optical bar fraction for S0 galaxies (47±11%) is consistent with the projection-corrected bar fraction (42±7%) from T81. T81 also finds that the (corrected) optical bar fraction for S0s decreases from 42±7% in the Coma core to 22±3% in the outskirts and outer regions of Coma. We cannot test the latter result directly as we do not have ACS data in the Coma outskirts. However, we see from Table 2 that while the optical bar fraction for S0s shows only a modest variation across low-to-intermediate density environments (field to intermediate-density clusters; last 3 rows of Table
Table 2. Optical bar fraction $f_{\text{bar-opt}}$ for different environments.

| Study          | Environment                  | S0                   |
|----------------|------------------------------|----------------------|
| this work      | Coma core, $z \sim 0.02$    | 47±11% (upper limit) |
| T81            | Coma core, $z \sim 0.02$    | 34±6%$^a$            |
| T81            | Coma core, $z \sim 0.02$    | 42±7%$^b$            |
| M09            | A901/902 clusters, $z \sim 0.165$ | 25±10%            |
| G10            | Virgo, $z \sim 0$           | 36±9%                |
| A09            | field–intermediate, $z \sim 0.01–0.04$ | 29%                |

$a$: from raw galaxy counts

$b$: after correcting galaxy counts for projection effects

1), it can be higher by up to a factor of $\sim 2$ in the very high-density environment of the rich Coma cluster core.

Finally, in Fig. 1d we show the semi-major axis $a_{\text{bar}}$ and the strength (ellipticity) $e_{\text{bar}}$ of the 10 bars we identified in the core of Coma. While the number statistics are very small, it is interesting that we do not find any large bars ($a_{\text{bar}} > 2$ kpc), as is seen in S0s in less dense environments. This may reflect evolutionary processes among S0s and bars in the dense environment of the Coma cluster core.

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Figure 1. (a) Absolute magnitude distribution in F814W (I band) for all 470 cluster members and morphological sub-types. In the category ‘other’ we include two galaxies classified as ‘peculiar’, two that are partially off the edge of a tile, and one distorted merger remnant. (b) Morphology distribution of our sample of disk galaxies. Most of the disks are S0s. (c) Barred galaxies identified through ellipse fitting and visual inspection (marked ‘vis’). (d) Distributions of $a_{\text{bar}}$ (top) and $c_{\text{bar}}$ (bottom).