The clustering of barred galaxies in the local Universe

Cheng Li,[1,2]★ Dimitri A. Gadotti,[1] Shude Mao[3] and Guinevere Kauffmann[1]

[1]*Max-Planck-Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany*
[2]*MPA/SHAO Joint Center for Astrophysical Cosmology at Shanghai Astronomical Observatory, Nandan Road 80, Shanghai 200030, China*
[3]*Jodrell Bank Centre for Astrophysics, Alan Turing Building, University of Manchester, Manchester M13 9PL*

ABSTRACT

We study the clustering properties of barred galaxies using data from the Sloan Digital Sky Survey. We compute projected redshift-space two-point cross-correlation functions $w_p(r_p)$ for a sample of nearly 1000 galaxies for which we have performed detailed structural decompositions using the methods described in Gadotti. The sample includes 286 barred galaxies. The clustering of barred and unbarred galaxies of similar stellar mass is indistinguishable over all the scales probed ($\sim$20 kpc–30 Mpc). This result also holds even if the sample is restricted to bars with bluer $g - i$ colours (and hence younger ages). Our result also does not change if we split our sample of barred galaxies according to bar-to-total luminosity ratio, bar boxyness, effective surface brightness, length or the shape of the surface density profile within the bar. There is a hint that red, elliptical bars are more strongly clustered than red and less elliptical bars, on scales $\gtrsim$1 Mpc, although the statistical significance is not high. We conclude that there is no significant evidence that bars are a product of mergers or interactions. We tentatively interpret the stronger clustering of the more elliptical bars as evidence that they are located in older galaxies, which reside in more massive haloes.

Key words: galaxies: distances and redshifts – cosmology: theory – dark matter – large-scale structure of Universe.

1 INTRODUCTION

It has long been known that stellar bars are very common in spiral galaxies. In the local Universe, about 30 per cent of disc galaxies have strong bars; this fraction increases to ~60 per cent if weak bars are included (e.g. de Vaucouleurs 1963; Knapen, Shlosman & Peletier 2000; Marinova & Jogee 2007). The bar is believed to play an important role in triggering the secular evolution of the galaxy (see e.g. Sellwood & Wilkinson 1993; Kormendy & Kennicutt 2004 for a review) and regulating star formation (e.g. Wang et al. 2006).

The redshift evolution of the bar fraction is still somewhat controversial. Several early studies of the bar fraction at $z > 0.5$ in the *Hubble Deep Fields* (HDFs) found a dramatic paucity of barred galaxies (Abraham et al. 1996, 1999; van den Bergh et al. 1996), although this result has been disputed by others (Sheth et al. 2003; Elmegreen, Elmegreen & Hirst 2004; Jogee et al. 2004; Zheng et al. 2005). An analysis by Sheth et al. (2008), which used a much larger sample, concludes that the bar fraction indeed decreases with redshift, with the effect being stronger for low-mass galaxies.

Two mechanisms are thought to contribute to the formation of bars. Bars can form through the $m = 2$ mode global instability in cold, rotationally supported discs. This has been demonstrated

by numerical simulations (e.g. Hohl 1971; Ostriker & Peebles 1973; Sellwood 1981; Athanassoula & Sellwood 1986). The other formation mechanism is through tidal perturbations by neighbouring galaxies. This has also been demonstrated using numerical simulations (Byrd et al. 1986; Noguchi 1987, 1988, 1996; Gerin, Combes & Athanassoula 1990; Miwa & Noguchi 1998). The effects induced by merging galaxies are quite complex. Simulations of the secular evolution of disc galaxies by Debattista et al. (2006) showed that interactions can speed up bar formation in direct encounters, but have little effect in retrograde ones (Toomre & Toomre 1972; Noguchi 1987; Gerin, Combes & Athanassoula 1990; Steinmetz & Navarro 2002; Aguerri & González-García 2009). Furthermore, it is possible for mergers to destroy or severely weaken the bar, without destroying the disc (Berentzen et al. 2003). It is thus not entirely clear what the combined effect of interactions and mergers is. Observationally, examples of tidally triggered bars are known (e.g. Debattista, Corsini & Aguerri 2002; Peirani et al. 2009). In addition, Elmegreen, Elmegreen & Bellin (1990) found an excess of binary companions in barred galaxies.

There is little doubt that both internally and externally driven mechanisms can trigger the formation of bars. We would like to determine empirically the relative importance of the two mechanisms, and also investigate whether we can differentiate bars formed through these two mechanisms. Miwa & Noguchi (1998) studied the difference between tidally induced bars and those induced by

internal processes, and concluded that the tidal effects produce slowly rotating bars while those arising from internal processes rotate much faster. Clearly these theoretical predictions need to be tested observationally.

In this paper, we select carefully a sample of nearby ($z < 0.07$) face-on galaxies from the Sloan Digital Sky Survey (SDSS; York et al. 2000), determine their structural properties with sophisticated imaging fitting and perform cross-correlation of barred galaxies with other galaxies in order to assess the importance of tidal interactions for the bar formation. The outline of the paper is as follows. In Section 2, we describe how our barred galaxies are selected and how their properties are measured. In Section 3 we present the method of our cross-correlation analysis. The main results are presented in Section 4. In Section 5 we briefly summarize our results and discuss their implications. Throughout this paper, we use a cosmology with a density parameter of $\Omega_m = 0.3$, and cosmological constant $\Omega_\Lambda = 0.7$ and the Hubble constant is written as $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2 DATA

The sample used for the classification of galaxies into barred and unbarred subclasses was drawn from a volume-limited sample in SDSS Data Release 2 (DR2; Abazajian et al. 2004), with $0.02 \leq z \leq 0.07$. To ease the identification of bars, the sample is restricted to galaxies very close to a face-on projection, i.e. with an axial ratio $b/a \geq 0.9$, where a and b are, respectively, the semimajor and semiminor axes of the galaxy. We excluded all galaxies with stellar masses below $10^{10}\,\mathrm{M_\odot}$, since dwarf galaxies are not object of our study. Galaxy stellar masses were obtained from Kauffmann et al. (2003). These criteria resulted in a sample of 3375 objects. The images of each of these galaxies were individually inspected to remove from the sample galaxies which are either not truly face-on, morphologically disturbed, too faint or irregular, too close to the border of the CCD frame, as well as duplicate entries and images where the presence of a bright star hinders the decomposition. We also rejected galaxies with apparent size smaller than ∼20 pixels across (∼8 arcsec), deemed too small for parametric image decomposition. The resulting sample contains 930 galaxies. We have verified that this sample is a fair representation of the galaxy population in this mass range in the local Universe (see Gadotti 2009).

To verify whether a galaxy is barred, we inspected the galaxy image, isophotal contours and a pixel-by-pixel radial intensity profile. We looked for typical bar signatures, i.e. an elongated structure with constant position angle and a flat ledge in the profile (see e.g. Gadotti et al. 2007). It should be noted that due to the limited spatial resolution of SDSS images, we miss most bars with semimajor axis shorter than ≈2–3 kpc, which are found mainly in very late-type spirals (later than Sc; Elmegreen & Elmegreen 1985). These faint bars lie typically within two–four seeing elements and do not produce clear signatures. The results presented here thus pertain to the typical, bona fide bars seen in early-type spirals and lenticulars. For each bar in our sample, we have measured a variety of properties through parametric image fitting. These include absolute magnitudes in g, r and i bands, optical colours defined by the three bands, effective surface brightness, effective radius, Sersic index, ellipticity, semimajor axis, boxyness and bar-to-total luminosity ratio. Details can be found in Gadotti (2009).

In this paper we classify all the galaxies into three types according to their bulge-to-total luminosity ratio B/T and bar-to-total luminosity ratio b/T. A galaxy is *elliptical* if $B/T = 1$; otherwise it is a *spiral* galaxy. In the latter case, the galaxy is further classified as

either *barred* if $b/T > 0$ or *unbarred* if $b/T = 0$. This results in 255 ellipticals, 389 unbarred and 286 barred spirals. We will use the last two samples when comparing barred and unbarred galaxies, and will use the barred sample on its own for investigating whether bar properties are sensitive to the environments of their host galaxies.

3 METHODS

We probe the clustering properties of our galaxies using the projected redshift-space two-point cross-correlation function (2PCCF), $w_p(r_p)$. We calculate the cross-correlation between the sample of galaxies for which we have detailed structural information from image decompositions and a reference sample of galaxies selected from the main spectroscopic sample of the Data Release 4 (DR4; Adelman-McCarthy et al. 2006) of the SDSS. A random sample is constructed so as to have the same selection effects as the reference sample. The reference and random samples are cross-correlated with the same set of galaxies in our sample, and $w_p(r_p)$ as a function of the projected separation r_p is defined by the ratio of the two pair counts minus one. Details about our methodology for computing the correlation functions and for constructing the reference and random samples can be found in Li et al. (2006). For consistency, we restrict our reference galaxies to the same redshift range as our sample with structural information, that is, $0.02 \leq z \leq 0.07$.

The amplitude of 2PCCF on scales larger than a few Mpc provides a direct measure of the mass of the dark matter haloes that host the galaxies through the halo mass–bias relation. As shown in Li et al. (2008a,b), the amplitude of the correlation function on scales ≲100 kpc can serve as a probe of physical processes such as mergers and interactions. On intermediate scales, the correlation probes the so-called '1-halo' term where the pair counts are dominated by galaxy pairs in the same halo.

4 RESULTS

4.1 Comparison between barred and unbarred galaxies

In the left-hand panel of Fig. 1, we compare projected redshift-space 2PCCF $w_p(r_p)$ for our samples of ellipticals, and spirals with and without bars. Results for the three samples are plotted as squares, triangles and circles, respectively, connected by the dashed, solid and dotted lines. This panel shows that elliptical galaxies are more
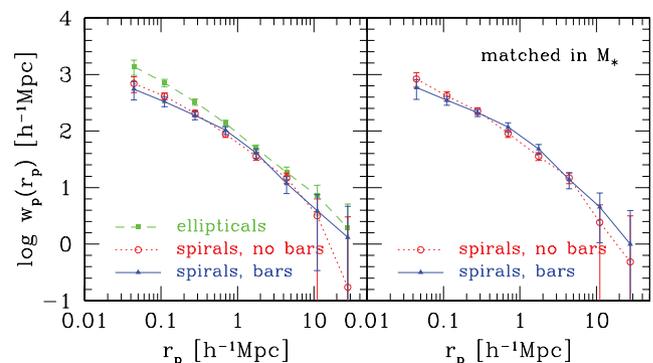
Figure 1. Projected redshift-space 2PCCF $w_p(r_p)$ for elliptical galaxies (green squares connected by the dashed line), the unbarred spiral galaxies (red circles connected by the dotted line) and the barred galaxies (blue triangles connected by the solid line). The right-hand panel shows the results for the barred and unbarred spiral samples only, but the samples are closely matched in stellar mass.
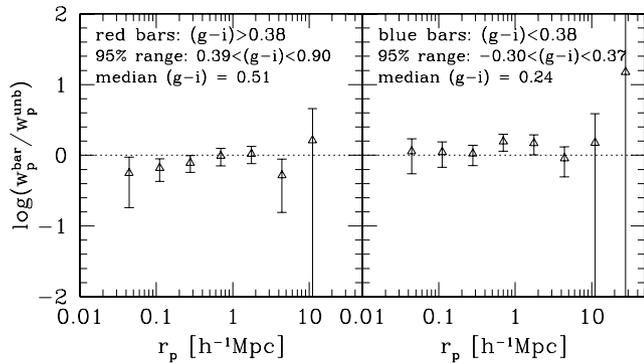
Figure 2. Ratio of $w_p(r_p)$ for red (left-hand panel) and blue (right-hand panel) bars relative to that for unbarred spirals. In each panel the barred and unbarred samples are closely matched in stellar mass. The median and the 95 per cent range of the $(g-i)$ colour of the bars are indicated.

strongly clustered than the other two types of galaxies, which is not surprising. This panel also shows that barred and unbarred spirals cluster in the same way. The right-hand panel shows the results for the two spiral samples again, but now the samples are closely matched in stellar mass M_*. Because clustering is known to depend on M_* it is important to control for this effect when investigating the dependence on other galaxy properties. There are still no significant differences between the two samples.

We tentatively conclude that the presence of a bar is not related to galaxy environment. In order to test whether the same conclusion holds for bars that have formed more recently, we thus split the barred spirals into two equal-size subsamples according to the $g - i$ colour of the bar. Gadotti & de Souza (2006, and references therein) suggest that bar colour can be used as a proxy for its dynamical age (but see Pérez, Sánchez-Blázquez & Zurita 2009). The results are shown in Fig. 2, where we compare $w_p(r_p)$ for galaxies with red (left-hand panel) or blue (right-hand panel) bars, together with the result for unbarred spirals. In each panel, the two samples are matched in stellar mass. We conclude that the colour of the bar has no effect on our main result.

We would also like to test whether our result is independent of the morphological type of the galaxy. For instance, Giuricin et al. (1993) found that the spirals in high-density environments tend to be barred only if they are early type. We have split the barred sample by M_* and by B/T, and the results are shown in Fig. 3. We have also checked the results for our subsamples of red and blue bars. In any case we see no dependence in clustering. We thus conclude that environment has no influence on whether or not bars are present in galaxies.

4.2 Dependence on bar properties

In this section we focus on the barred galaxies and study the dependence of clustering on the properties of the bars. As in the previous section, we split the galaxies into two subsamples at the median value of the given property. We also trim the two samples so that they each have the same distribution in stellar mass.

The results are shown in Fig. 4, where we plot in each panel the ratio of the measurement of $w_p(r_p)$ for barred galaxies with higher and lower values of the given bar property. The left-hand panels show results for all the bars in our sample, while the following two panels are for red and blue bars. The bar properties we consider are (from top to bottom) bar-to-total luminosity ratio, ellipticity, boxyness, effective surface brightness, length of the semimajor axis
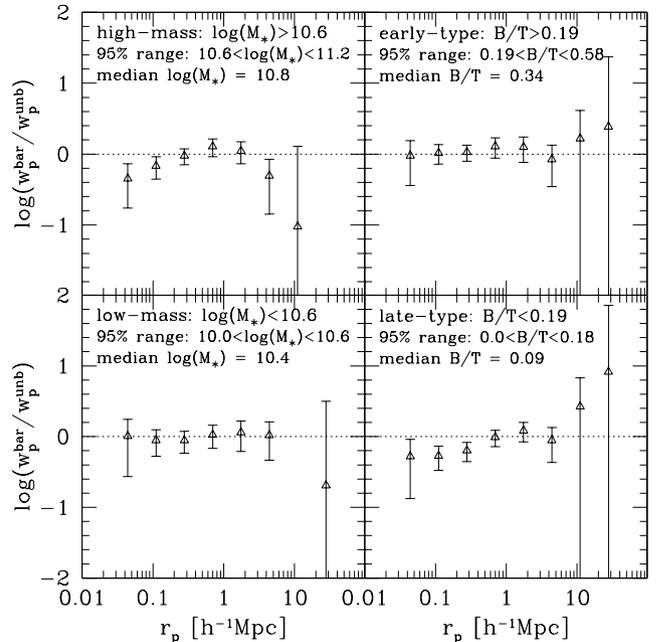
Figure 3. Ratio of $w_p(r_p)$ for all bars with respect to unbarred spirals. The bars are divided into two equal-size subsamples according to either the stellar mass or the bulge-to-total luminosity ratio of their host galaxies, and the results are shown in the upper left-hand panel for the high-mass subsample, in the lower left for the low-mass subsample, in the upper right for the early-type subsample and in the lower right for the late-type subsample. In each panel the barred and unbarred samples are closely matched in stellar mass. The median and the 95 per cent range of stellar mass or bulge-to-total luminosity ratio are indicated.

and Sersic index (see Section 2 for detailed description on these quantities).

From Fig. 4 we see some indications of dependence of bar properties on clustering, however, they are not very significant due to the large errors in the $w_p(r_p)$ measurements resulting from small sample sizes. These include the bar ellipticity, bar-to-total luminosity ratio and Sersic index for red bars.

Interestingly, there is a hint of bar ellipticity dependence on clustering. For the sample as a whole, the difference in clustering occurs on scales greater than $\sim 1\, h^{-1}$ Mpc. High-ellipticity bars are more strongly clustered than low-ellipticity bars on large scales. When the bars are divided into red and blue subsamples, the (weak) effect persists for the red bars but largely vanishes for the blue bars.

One possible explanation for these trends (if confirmed with larger samples) is that more elliptical bars occur in older, more evolved galaxies. The age of a galaxy of fixed stellar mass will be larger in more massive haloes than less massive ones, so one would expect to see clustering differences of the kind that we observe. The dependence of bar ellipticity on age is predicted both from N-body simulations and analytical work (see for example Athanassoula & Misiriotis 2002; Athanassoula 2003). It would be interesting to examine the ellipticity dependence on clustering with larger samples in the future.

4.3 Dependence on local environment

The power of the $w_p(r_p)$ statistic is that it encapsulates information about how galaxy properties depend on environment over a wide range of physical scales, including both the regime of galaxy–galaxy interactions at scales below 100 kpc and the regime of local
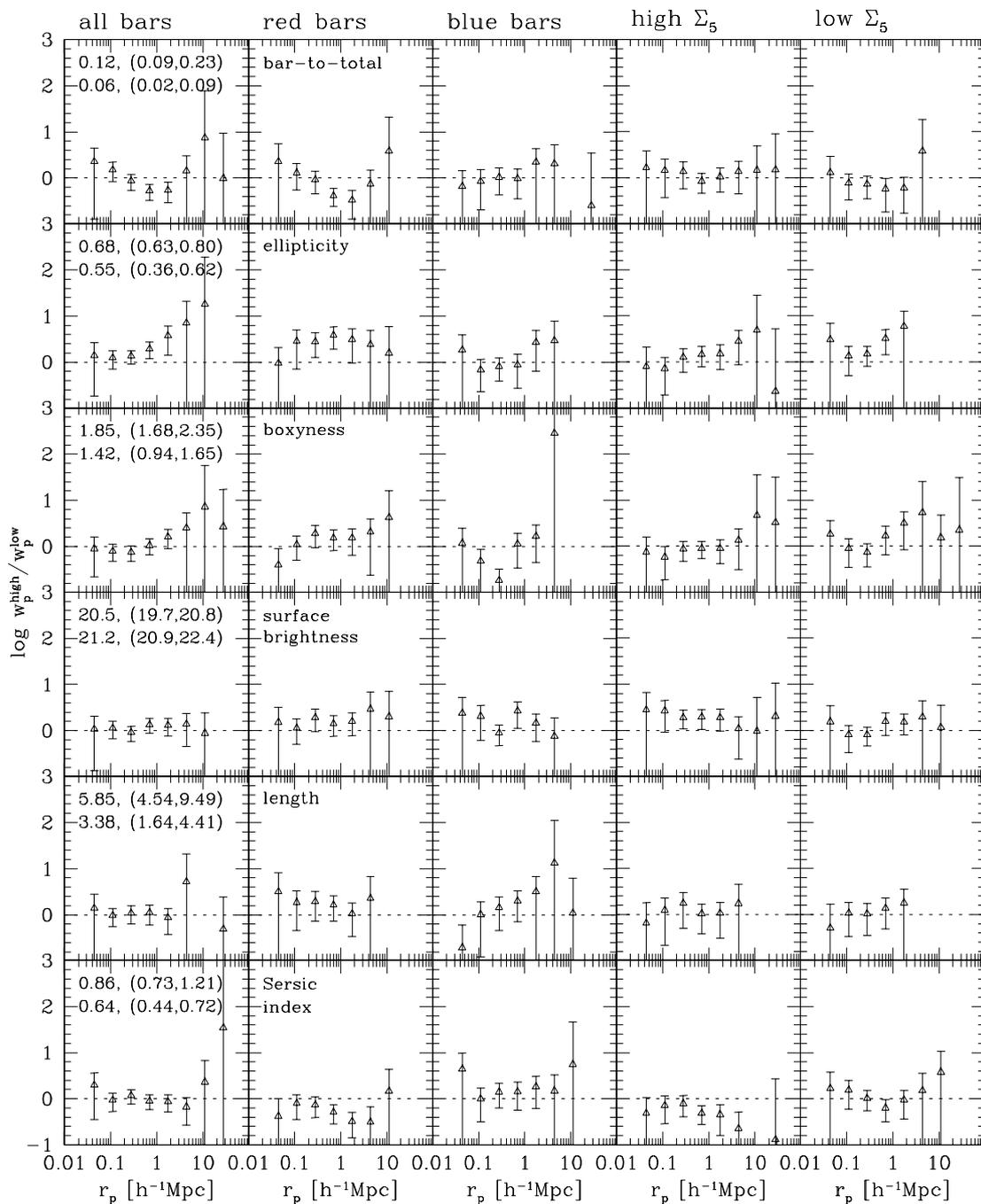
Figure 4. We test whether the projected redshift-space 2PCCF $w_p(r_p)$ depends on bar properties. Panels from left to right correspond to results for the whole bar sample, for subsamples of red and blue bars and for subsamples of bars located in high- and low-density regions. Panels from top to bottom test the dependence of the 2PCCF on the bar property as indicated. Each panel shows the ratio of $w_p(r_p)$ between two subsamples, which are matched in stellar mass, with higher and lower value of the property. The median and 95 per cent range of the bar property are indicated in the left-hand panels for the two corresponding subsamples.

environment at larger scales. There have also been a number of studies directly examining the correlations between the fractions and properties of bars in galaxies and their local environment (e.g. Aguerri, Méndez-Abreu & Corsini 2009). The local environment is usually expressed in terms of overdensities in galaxy number that are estimated in a fixed sphere/aperture centred on the galaxies being studied. The radius of the sphere/aperture is chosen to be less than a few Mpc so as to probe the physical processes occurring inside dark matter haloes.

In order to make comparisons with such studies as well as to understand the *real* environments of our galaxies, we have calculated local density using two different quantities that have been commonly adopted in previous studies. We first follow Kauffmann et al. (2004) and compute the number of galaxies N_c in the reference sample within $2\,h^{-1}$ Mpc in projected radius and $\pm 500\,\mathrm{km\,s^{-1}}$ in velocity difference from the galaxy being studied. We also follow Balogh et al. 2004 (see also Aguerri et al. 2009) and estimate a projected local density Σ_5 of each galaxy in our sample using the
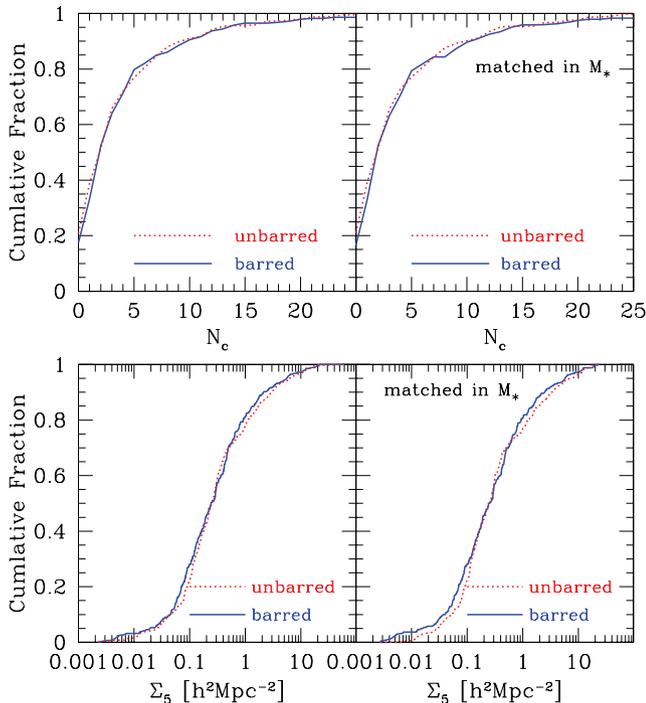
Figure 5. Cumulative distribution of barred (solid blue line) and unbarred (dashed red line) spiral galaxies as a function of the number of neighbour galaxies within $2\,h^{-1}$ Mpc in projected radius (top panels), and the local galaxy density Σ_5 (bottom panels) estimated using the projected distance to the fifth nearest neighbour galaxy (see text for details). In the right-hand panel the two samples are closely matched in stellar mass.

Figure 6. Ratio of $w_p(r_p)$ of bars relative to that of unbarred spirals. The left-hand (right-hand) panel is for galaxies with local density Σ_5 higher (lower) than $0.24\,h^2\,\mathrm{Mpc}^{-2}$, the median Σ_5 of the whole sample. In each panel the barred and unbarred samples are closely matched in stellar mass. The median and the 95 per cent range of the Σ_5 value of the bars are indicated.

projected distance d_5 to its fifth nearest neighbour galaxy within $\pm 1000\,\mathrm{km\,s^{-1}}$. For both quantities we only consider neighbouring galaxies that are brighter than $M_r = -20$ and not closer than $50\,h^{-1}$ kpc. The bright limit gives us a uniform density estimate that is applicable to our magnitude-limited sample over the full redshift range probed. The lower limit for projected distance is chosen such that the galaxy itself is not included in the density estimate and, more importantly, the density estimate is not biased by SDSS fibre collisions. It is important to note that, for these density calculations, we have constructed a new reference sample using the SDSS Data Release 7 (DR7; Abazajian et al. 2009) which covers much larger area on the sky than do our samples of barred/unbarred galaxies. By this way we have avoided for most of our galaxies the potential bias in the estimated densities due to edges and holes in the survey.

Fig. 5 shows the cumulative fraction of barred and unbarred galaxies in our sample as a function of N_c (upper panels) and Σ_5 (lower panels). Results are shown in the left-hand panels for the original samples, and in the right-hand panels after the two samples have been matched in stellar mass. Overall, only 20 per cent of our galaxies have no neighbours and around half have two or more neighbours. These numbers are in good agreement with those quoted in Kauffmann et al. (2004, see their fig. 1). Our estimates of Σ_5 also agree well with that of Aguerri et al. (2009, see their fig. 10). Around 80 per cent of the galaxies are located in underdense regions with $\Sigma_5 < 1\,h^2\,\mathrm{Mpc}^{-2}$. The median value of Σ_5 is 0.24 for the galaxies as a whole.

Fig. 5 shows that there is no significant correlation between the presence of a bar in the galaxies and their local densities. This is true no matter how the density is quantified and whether or not the
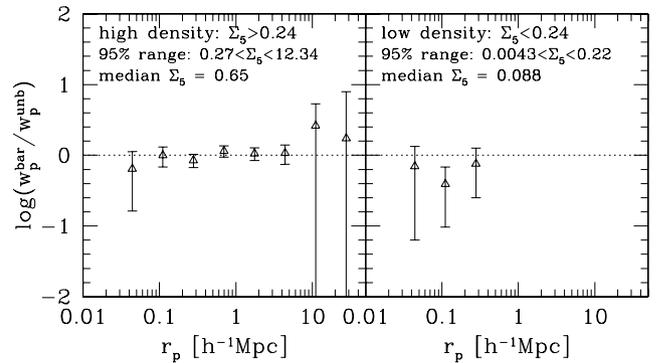
two comparison samples are matched in stellar mass. Our results again are well consistent with Aguerri et al. (2009), although they have treated the edge effect in a more careful way. After excluding galaxies at less than 7 Mpc from the nearest edge of SDSS, the authors still did not find any difference between the environment of barred and unbarred galaxies.

In Fig. 6 we compare the projected 2PCCF $w_p(r_p)$ for barred and unbarred samples, matched in stellar mass but with different local densities. For this we divide all the galaxies into two subsamples according to whether they are located in regions with Σ_5 higher or lower than $0.24\,h^2\,\mathrm{Mpc}^{-2}$, the median value of the whole sample. For each subsample, we then compute $w_p(r_p)$ for the barred and unbarred galaxies separately. Again we have trimmed the barred and unbarred samples so that they show similar stellar mass distributions. As can be seen from the figure there is still no difference between the clustering of barred and unbarred galaxies on all scales where we have $w_p(r_p)$ measurements.

In the last two columns in Fig. 4 we show the results for bars with different properties, but for those located in high and low densities separately. There is no significant effect anywhere.

5 SUMMARY AND DISCUSSION

We have used a sample of nearly 1000 galaxies (including 255 ellipticals, 389 unbarred and 286 barred spirals) from the SDSS with well-determined structural parameters to study the clustering properties of galaxies with bars in the low-redshift Universe. For the first time this is quantified by the projected redshift-space 2PCCF $w_p(r_p)$, which is computed over a range of scales from ~ 10 kpc to a ~ 10 Mpc. In practice, we cross-correlate the sample of galaxies with well-determined structural parameters with a large reference sample of galaxies drawn from full DR4 spectroscopic sample. The statistical errors on our results are acceptable due to the large size of the reference sample.

The measurement of $w_p(r_p)$ on all scales does not depend on the presence or absence of a bar. This is true when the bars are divided into subsamples according to their optical colours, a crude indicator of mean stellar age and possibly bar dynamical age, or when the host galaxies are divided according to stellar mass or bulge-to-total luminosity ratio. We have also examined the dependence of clustering on the properties of bars. These include the bar-to-total

luminosity ratio, bar morphology measured by ellipticity and boxy-ness and the surface brightness profile characterized by the effective surface brightness, length and Sersic index. In addition, we checked the clustering dependence on global galaxy properties such as size and mean stellar surface density. We find a stronger hint that the clustering depends only on ellipticity. Bars with high ellipticities appear to be more strongly clustered than those with low elliptici-ties on scales between ∼1 and $10\,h^{-1}$ Mpc, and this is true only for red bars.

On scales larger than a few Mpc, the amplitude of $w_p(r_p)$ directly measures the mass of the dark matter haloes that host the galaxies (e.g. Jing, Mo & Boerner 1998). Our results thus suggest that the formation and evolution of bars are independent of the mass of dark matter haloes in which their host galaxies are found. The amplitude of $w_p(r_p)$ on scales $\lesssim 100$ kpc probes physical processes such as mergers and interactions (e.g. Li et al. 2008a,b). Thus our results also suggest that the formation of bars is not dominated by external processes such as interactions with close companions.

Our results provide support that bars in the local Universe may be predominantly produced by global gravitational instability (Toomre 1981; Sellwood & Wilkinson 1993). Numerical simulations indi-cate that bars can form spontaneously in galactic discs, usually on relatively short time-scales. There is a hint of environmental effects on bar properties, for example the ellipticity of red bars which may be a consequence of the fact that bar ellipticity tends to increase with the age of the galaxy.

We now list a number of important caveats. First, our sample of bars, while larger than most previous studies, is still relatively small and the errors on our correlation function measurements are larger than we would like. Our sample is also biased towards strong (thus possibly old) bars and high-luminosity galaxies, and so our conclusions must also be limited to these galaxies. The blue bars in our sample, which are presumably 'young' (Gadotti & de Souza 2005, 2006), may be already old enough and we might have missed the connection with close companions due to this bias. Finally, galaxies associated with ongoing major mergers were excluded from our (visually selected) sample and so our $w_p(r_p)$ measurements are probably biased low at very small separations. The effect of this can be seen from the small-scale correlation functions. In all of our figures, we do not have $w_p(r_p)$ measurements at r_p below ∼40 kpc, indicating that we have been only able to probe galaxy–galaxy interactions with projected separations larger than this scale and have lost all closer systems.

Our results are consistent with van den Bergh (2002) who used the Palomar Sky Survey to classify 930 galaxies into field, group and cluster environments, and found that 25 ± 3, 19 ± 4 and 28 ± 3 per cent of galaxies were barred (i.e. there was no significant trend with environment). Our results are also consistent with Aguerri et al. (2009) who examined the relationship between bar properties and local galaxy density using 2106 disc galaxies from the SDSS and also concluded that the properties of bars do not depend on the local environment. Barazza et al. (2009) have recently compared the properties of bars in field and clusters using a sample of 925 galaxies at redshifts $z = 0.4$–0.8, and found that bars in clusters are slightly longer than that in field galaxies. However, given the different redshift ranges, the small sample sizes and the different sample selections, this discrepancy should not be overemphasized and needs to be revisited in the future with larger samples.

With the large number of galaxies in the SDSS, a much larger sample of barred galaxies can be constructed using more objective criteria (see e.g. Barazza, Jogee & Marinova 2008), including fainter galaxies and weaker bars. When such a sample becomes available,

it will be possible to have better statistics and more reliable results. We intend to return to this topic in our future work.

REFERENCES

Abazajian K. et al., 2004, AJ, 128, 502
Abazajian K. et al., 2009, ApJS, 182, 543
Abraham R. G., Tanvir N. R., Santiago B. X., Ellis R. S., Glazebrook K., van den Bergh S., 1996, MNRAS, 279, L47
Abraham R. G., Merrifield M. R., Ellis R. S., Tanvir N. R., Brinchmann J., 1999, MNRAS, 308, 569
Adelman-McCarthy J. K. et al., 2006, ApJS, 162, 38
Aguerri J. A. L., González-García A. C., 2009, A&A, 494, 891
Aguerri J. A. L., Méndez-Abreu J., Corsini E. M., 2009, A&A, 495, 491
Athanassoula E., 2003, MNRAS, 341, 1179
Athanassoula E., Misiriotis A., 2002, MNRAS, 330, 35
Athanassoula E., Sellwood J. A., 1986, MNRAS, 221, 213
Balogh M. et al., 2004, MNRAS, 348, 1355
Barazza F. D., Jogee S., Marinova I., 2008, ApJ, 675, 1194
Barazza F. D. et al., 2009, A&A, 497, 713
Berentzen I., Athanassoula E., Heller C. H., Fricke K. J., 2003, MNRAS, 341, 343
Byrd G. G., Valtonen M. J., Valtaoja L., Sundelius B., 1986, A&A, 166, 75
Debattista V. P., Corsini E. M., Aguerri J. A. L., 2002, MNRAS, 332, 65
Debattista V. P., Mayer L., Carollo C. M., Moore B., Wadsley J., Quinn T., 2006, ApJ, 645, 209
de Vaucouleurs G., 1963, ApJS, 8, 31
Elmegreen B. G., Elmegreen D. M., 1985, ApJ, 288, 438
Elmegreen D. M., Elmegreen B. G., Bellin A. D., 1990, ApJ, 364, 415

Elmegreen B. G., Elmegreen D. M., Hirst A. C., 2004, ApJ, 612, 191
Gadotti D. A., 2009, MNRAS, 393, 1531
Gadotti D. A., de Souza R. E., 2005, ApJ, 629, 797
Gadotti D. A., de Souza R. E., 2006, ApJS, 163, 270
Gadotti D. A., Athanassoula E., Carrasco L., Bosma A., de Souza R. E., Recillas E., 2007, MNRAS, 381, 943
Gerin M., Combes F., Athanassoula E., 1990, A&A, 230, 37
Giuricin G., Mardirossian F., Mezzetti M., Monaco P., 1993, ApJ, 407, 22
Hohl F., 1971, ApJ, 168, 343
Jing Y. P., Mo H. J., Boerner G., 1998, ApJ, 494, 1
Jogee S. et al., 2004, ApJ, 615, L105
Kauffmann G. et al., 2003, MNRAS, 341, 33
Kauffmann G., White S. D. M., Heckman T. M., Ménard B., Brinchmann J., Charlot S., Tremonti C., Brinkmann J., 2004, MNRAS, 353, 713
Knapen J. H., Shlosman I., Peletier R. F., 2000, ApJ, 529, 93
Kormendy J., Kennicutt R. C., Jr, 2004, ARA&A, 42, 603
Li C., Kauffmann G., Wang L., White S. D. M., Heckman T. M., Jing Y. P., 2006, MNRAS, 373, 457
Li C., Kauffmann G., Heckman T. M., Jing Y. P., White S. D. M., 2008a, MNRAS, 385, 1903
Li C., Kauffmann G., Heckman T. M., White S. D. M., Jing Y. P., 2008b, MNRAS, 385, 1915
Marinova I., Jogee S., 2007, ApJ, 659, 1176
Miwa T., Noguchi M., 1998, ApJ, 499, 149
Noguchi M., 1987, MNRAS, 228, 635
Noguchi M., 1988, A&A, 203, 259
Noguchi M., 1996, ApJ, 469, 605
Ostriker J. P., Peebles P. J. E., 1973, ApJ, 186, 467
Peirani S., Hammer F., Flores H., Yang Y., Athanassoula E., 2009, A&A, 496, 51
Pérez I., Sánchez-Blázquez P., Zurita A., 2009, A&A, 495, 775
Sellwood J. A., 1981, A&A, 99, 362
Sellwood J. A., Wilkinson A., 1993, Rep. Prog. Phys., 56, 173
Sheth K., Regan M. W., Scoville N. Z., Strubbe L. E., 2003, ApJ, 592, L13
Sheth K. et al., 2008, ApJ, 675, 1141
Steinmetz M., Navarro J. F., 2002, New Astron., 7, 155
Toomre A., 1981, in Fall S. M., Lynden-Bell D., eds, The Structure and Evolution of Normal Galaxies. Cambridge Univ. Press, Cambridge, p. 111
Toomre A., Toomre J., 1972, ApJ, 178, 623
van den Bergh S., 2002, AJ, 124, 782
van den Bergh S., Abraham R. G., Ellis R. S., Tanvir N. R., Santiago B. X., Glazebrook K. G., 1996, AJ, 112, 359
Wang J. L., Xia X. Y., Mao S., Cao C., Wu H., Deng Z. G., 2006, ApJ, 649, 722
York D. G. et al., 2000, AJ, 120, 1579
Zheng X. Z., Hammer F., Flores H., Assémat F., Rawat A., 2005, A&A, 435, 507

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