Radio and optical orientations of galaxies

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ABSTRACT

We investigate the correlations between optical and radio isophotal position angles for 14,302 Sloan Digital Sky Survey galaxies with $r$ magnitudes brighter than 18 and which have been associated with extended Faint Images of the Radio Sky at Twenty centimetres (FIRST) radio sources. We identify two separate populations of galaxies using the colour, concentration and their principal components. Surprisingly, strong statistical alignments are found: late-type galaxies are overwhelmingly biased towards a position angle differences of $0^\circ$ and early-type galaxies to $90^\circ$. The late-type alignment can be easily understood in terms of the standard picture in which the radio emission is intimately related to areas of recent star formation. In early-type galaxies, the radio emission is expected to be driven by accretion on to a nuclear black hole. We argue that the observed correlation of the radio axis with the minor axis of the large-scale stellar distribution gives a fundamental insight into the structure of elliptical galaxies, for example, whether or not the nuclear kinematics are decoupled form the rest of the galaxy. Our results imply that the galaxies are oblate spheroids with their radio emission aligned with the minor axis. Remarkably, the strength of the correlation of the radio major axis with the optical minor axis depends on radio loudness. Those objects with a low ratio of FIRST radio flux density to total stellar light show a strong minor axis correlation while the stronger radio sources do not. This may reflect different formation histories for the different objects, and we suggest we may be seeing the different behaviour of slow rotating and fast rotating ellipticals. A simple analysis to estimate the effects of measurement errors indicates that the intrinsic degree of anti-alignment in the roundest early-type galaxies may be as small as $\pm 15^\circ$ and a similar value is obtained for the degree of alignment in the late-type population.

Keywords: galaxies: elliptical and lenticular, cD – galaxies: general – galaxies: jets – galaxies: statistics – galaxies: structure – radio continuum: general.

1 INTRODUCTION

There has been a long history of searching for alignments between the structures of radio sources and those of their host galaxies and generally the results have been inconclusive (e.g. Mackay 1971; Palimaka et al. 1979; Valtonen 1983; Birkinshaw & Davies 1985; Sansom et al. 1987), though in most investigations there appear to be a preponderance of objects where the radio elongation is more aligned with the optical minor axis than the major axis. The clearest result was obtained by Condon, Frayer & Broderick (1991) who found that extended radio jets in 125 UGC galaxies were preferentially aligned with the optical minor axes of their hosts, with the effect being strongest for elliptical galaxies. Other, related investigations, have focused on the relative orientation of radio axes and dust discs (e.g. Schmitt et al. 2002) and these again show a broad distribution with no obvious preferred alignment. Such studies were motivated by the desire to find a connection between radio emission mechanism and the geometry of the host galaxy. The historic results have been based on relatively small numbers of objects (∼100), but with the advent of deep radio and optical surveys like Faint Images of the Radio Sky at Twenty centimetres (FIRST; Becker, White & Helfand 1995) and the Sloan Digital Sky Survey (SDSS; York et al. 2000), respectively, it is possible to construct samples with orders of magnitude larger numbers. This means going deeper in radio flux density to get better statistics and an unavoidable consequence is that the galaxies identified with the radio sources are no longer dominated by the ellipticals, which were the targets of early studies, but are now a mixture of ellipticals and disc-dominated star-forming galaxies. Since the source of the emission is fundamentally different in the two types of galaxy, one might well expect their alignment properties also to be different. For example, it is known from studies of nearby star-forming galaxies that the radio emission traces the distribution of recent star formation (Condon 1992 and references therein; Murphy et al. 2008) and therefore, assuming one has observations with the appropriate resolution, one might expect to see a statistical alignment between the radio emission and the starlight.
On the other hand, radio emission in the elliptical population is likely to be powered by the nuclear black hole and the alignment of the resulting jets/lobes will contain information about the nucleus of the galaxy. In the light of the existence of kinematic substructures, including decoupled cores, in a significant fraction of early-type galaxies (e.g. Halliday et al. 2001; Loubser et al. 2008; Krajnović et al. 2008), and the separation of such galaxies into two distinct classes the fast and slow rotators (Emsellem et al. 2007), studying the alignment between the stellar population and the radio emission assumes added significance.

In this paper, we examine the statistics of the alignments of radio and optical structures using radio data from the FIRST survey (Becker et al. 1995) which has a resolution 5 arcsec and optical data for the identifications from SDSS (York et al. 2000). Star formation, and its associated radio emission, tends to be concentrated in the inner few kpc of galaxies (e.g. Condon 1992; Muxlow et al. 2005; Wilman et al. 2008). Thus, one might expect such emission to be just resolved in most FIRST radio maps of star-forming galaxies with low redshift (≤0.2). In such galaxies, optical elongations should be available in SDSS and thus the FIRST/SDSS combination is well suited to the task. For the other major component of the mJy radio population, the jet-powered radio galaxies, FIRST data are also useful but for a more restricted set of objects because of the wide dispersion in their linear sizes. The advantage of using SDSS is the wealth of photometric and spectroscopic data that can be used to separate intrinsically different populations of galaxies, and we exploit this extensively in what follows.

Our motivations for this work are to learn more about the mechanisms behind the alignments and to elucidate the statistical properties of the low-luminosity radio emitters which will dominate the populations of radio sources discovered in new deeper radio surveys like Low-Frequency Array, Square Kilometre Array (SKA) pathfinders and the SKA itself. There is the possibility that the extended radio emission from star-forming galaxies might be used for weak lensing studies (Blake et al. 2003), and it is interesting to investigate properties of the observed galaxy alignments when compared to the optical.

2 SAMPLE SELECTION

We use optical identifications of FIRST radio sources listed in the SDSS Data Release 6 (DR6) data base (Adelman-McCarthy et al. 2008) which were selected using the procedure defined in Ivezić et al. (2002). There are 239993 such identifications which were extracted from the SDSS data base using SQL. We have also extracted the photometric model magnitudes from SDSS (ugriz), the integrated flux density measured by FIRST ($S_{\text{First}}$), the position angle (PA; $\alpha$ defined between ~90° and 90° and measured from north through east) computed from the isophotal distribution in the r band by SDSS along with the equivalent from FIRST, the major ($a$) and minor ($b$) axes measured by SDSS and FIRST, and $R_{50}$ and $R_{90}$ measured from the Petrosian intensity profile model fitted to the SDSS images (Petrosian 1976). The quantity $c = R_{90}/R_{50}$ is known as the concentration; for small c, the light distribution has an exponential profile and fits the profile of a disc galaxy, whereas for large values of c the profile is approximated by a de Vaucouleurs profile which is often used to model the light distribution of an elliptical galaxy.

For our investigation, we require galaxies and radio sources for which there are reliable measures of the PA of extended emission. In order to produce a statistically robust sample, we have imposed additional selection criteria. First, we have excluded all galaxies which are classified as ‘stellar’ by the SDSS pipeline. Such galaxies are likely to be at high redshift and will be almost circular from the point of view of the SDSS beam, making computation of a meaningful PA impossible. It will also be difficult to compute the PA accurately for very faint galaxies, those with large axial ratios ($b/a$) and those where the major axes are significantly smaller than the beam. We have excluded all galaxies with $r > 18$, $b/a > 0.8$ in either SDSS or FIRST and those with $a < 2$ arcsec in FIRST. This leaves a total of 14302 galaxies on which we have performed our analysis. The size of this sample is around two orders of magnitude larger than previous studies and it contains a range of galaxy types.

We have decided to use the r-band PA since they are computed from the images which typically have the highest signal-to-noise ratio. In Fig. 1, we present histograms of the acute angle between the PA measured in the next two most sensitive bands, i and g, for the sample with $r < 18$. It can be seen that there is very good agreement between them. Relaxation of the limit on $r$ degrades this agreement, whereas imposing a more severe cut-off would produce an even tighter correlation between the PA measured in different bands. We have also plotted the difference between the $r$ and $i$ band PA as a function of $b/a$ in Fig. 2. It shows that, as one would expect, the noise on measurement of the PA is lower for objects with much better defined PA, i.e. those which have small axial ratios.

3 RESULTS

3.1 Whole sample

In what follows, we will present histograms of the galaxies in the sample binned according to the quantity $\Delta \alpha$, defined to be the acute angle between the two PA $\alpha_{\text{SDSS}}$ and $\alpha_{\text{FIRST}}$. The results for a histogram of 18 bins are presented in Fig. 3, along with the individual distributions for $\alpha_{\text{SDSS}}$ and $\alpha_{\text{FIRST}}$. There is a clear excess

![Image](https://academic.oup.com/mnras/article-abstract/399/4/1888/1033827)}
Figure 2. The percentage of galaxies against the PA difference measured in the $r$ and $u$ bands as a function of axial ratio $b/a$. The solid line has $0.6 < b/a < 0.8$, dotted line $0.4 < b/a < 0.6$ and dashed line $b/a < 0.4$. The equivalent histogram for all values of the axial ratio is the dashed line in Fig. 1.

Figure 3. Histograms of $\Delta \alpha$ (bottom panel), $\alpha_{SDSS}$ (middle panel) and $\alpha_{FIRST}$ (top panel) using 18 bins for all 14,302 galaxies. Included also are the Poisson errors for each bin. Note the peak at $\Delta \alpha = 0$ and those at $\alpha_{FIRST} \approx \pm 30^\circ$ and $\pm 90^\circ$. The histogram for $\alpha_{SDSS}$ is consistent with a uniform distribution.

Figure 4. Equivalent to Fig. 3 but for six bins. The peak at $\Delta \alpha = 0$ remains but those in $\alpha_{FIRST}$ are smeared out. The distribution of $\alpha_{FIRST}$ is still not compatible with a uniform distribution.

Figure 2. The percentage of galaxies against the PA difference measured in the $r$ and $u$ bands as a function of axial ratio $b/a$. The solid line has $0.6 < b/a < 0.8$, dotted line $0.4 < b/a < 0.6$ and dashed line $b/a < 0.4$. The equivalent histogram for all values of the axial ratio is the dashed line in Fig. 1.

The histogram of $\alpha_{SDSS}$ is compatible with a uniform distribution $\chi^2 \approx 1.1$. By contrast, that for $\alpha_{FIRST}$ appears to have statistically significant peaks at $\pm 30^\circ$ and to a lesser extent at $\pm 90^\circ$. The peaks are clearly systematics associated with the extraction of PA from the images produced the FIRST survey. Chang, Refregier & Helfand (2004) have searched for cosmic shear signal due to weak gravitational lensing using the data from the FIRST survey. They pointed out a number of subtle systematic effects which had to be removed from the images in order to make an accurate measurement of cosmic shear. These effects are small at the level of an individual source, but since they are systematic they can be seen in global statistics such as those used to study cosmic shear. They also show up in the histogram presented in Fig. 3. However, our interest is in PA differences, $\Delta \alpha$, and for systematics in one set of angles to have a significant effect they would have to be correlated with systematics in the other set of angles. Since the SDSS angle distribution is nearly uniform, it is unlikely that such systematics will have a significant effect on our results. Moreover, as we will see later, some of our most interesting results are that the observed PA distributions depend strongly on the physical properties of the objects, and this cannot arise from measurement systematics.
Nevertheless, to reassure ourselves of the robustness of our results we have performed some tests. We have selected a subset of FIRST sources to have a completely flat distribution of PA and also divided the original sample into different areas and looked for different systematics in different areas of sky. We still see similar biases to those in Fig. 3 in the PA differences in the sample in which the FIRST PA distribution is flat. In the second test, we find that the FIRST PA distribution is roughly the same independent of where we look in the sky.

3.2 Split on colour and concentration

It is natural to split the sample based on photometric determined parameters such as colour and concentration. It has been shown by Strateva et al. (2001) that the colour defined by $u - r$ can discriminate between different distributions in the bimodal $g - r$ versus $u - g$ colour–colour diagram for an earlier SDSS DR. Based on morphological identifications of nearby galaxies, they suggest that $u - r = 2.22$ is the optimal colour separator and then go on to show this split can be linked directly to two populations, early-type galaxies (E, S0, Sa) which have $u - r > 2.22$ and late-type galaxies (Sb, Sc, Irr) with $u - r < 2.22$. We have examined the properties of the correlation between $\sigma_{\text{SDSS}}$ and $\sigma_{\text{FIRST}}$ as a function of $u - r$. Specifically, we constructed histograms as a function of $u - r$ with bin width $\Delta(u - r) = 0.5$ and searched for obvious trends. We find that the peak in the histogram at $\Delta\alpha = 0^\circ$ is apparent for low values of $u - r$ (blue objects), whereas the histograms for higher values of $u - r$ (red objects) are peaked at $\Delta\alpha = 90^\circ$ (correlation between the SDSS major axis and the FIRST minor axis, or vice versa). In Fig. 5, we have split the sample into subsamples with $u - r < 3$, 8933 galaxies, and $u - r > 3$, 5369 galaxies. This appears to be close to optimal in terms of separating the two effects. For $u - r < 3$, we have that $\chi^2 \approx 212$, whereas $\chi^2 \approx 3.6$ for $u - r > 3$. Clearly, the observed correlation for blue half of the galaxy sample is extremely strong, but that for red half is also statistically significant. The precise cut which we have used is interesting since Strateva et al. (2001) showed that for $u - r > 3$ the sample would be dominated by elliptical morphologies (including S0s) with little contamination from spirals. We have also performed a split on concentration which as discussed in Strateva et al. (2001) can also crudely distinguish between different galaxy types. Using a similar approach to the case of colour, we have identified $c = 3$ as being close to the optimal in separating the two effects already noted above. Fig. 5 shows histograms for $c < 3$, 8803 galaxies, and $c > 3$, 5499 galaxies. The two samples have $\chi^2 \approx 215$ and 2, respectively. The peak at $\Delta\alpha = 90^\circ$ for $c > 3$ is less significant than the corresponding one when colour selection is used, suggesting that there is a little more cross-contamination of the sample when using concentration as a discriminator.

On the basis of these two simple splits, we are already led to the basic conclusions of this work: blue, less concentrated galaxies, which broadly represent the disc-dominated, spiral population, have the optical and radio major axes correlated, whereas at least some fraction of red, highly concentrated galaxies, which are part of the elliptical population, have a correlation between the optical major and radio minor axes. In the subsequent sections, we will attempt to refine the selection process using other measured properties of these galaxies. The aim is to strengthen the correlations as quantified by the value of $\chi^2$ and to obtain a physical insight as to their origin.

3.3 Principal component analysis

The colour and concentration are known to be correlated (see e.g. Strateva et al. 2001). In Fig. 6, we illustrate this for our sample by presenting a scatter plot of $u - r$ and $c$ which clearly shows the degeneracy between these two properties. There is also a bimodality in the density of points in this plot, suggesting that there are indeed two populations within the sample.

In order to investigate this quantitatively, we have performed a principal component analysis (PCA) on the sample, initially with two variables $u - r$ and $c$. The two components which are generated...
by this procedure are
\[ C_1 = 0.965c - 0.262(u - r), \]
\[ C_2 = 0.262c + 0.965(u - r). \]  

Figure 7. Various splits of the data determined on the basis of the PCA analysis and the axial ratio: (bottom-left panel) \( C_2 < 3.5 \); (top-right panel) \( C_2 > 3.5 \); (top-left panel) \( C_2 > 3.5 \) and \( b/a < 0.6 \); (right-panel) \( C_2 > 3.5 \) and \( b/a > 0.6 \).

\[ \Delta \alpha = 0^\circ \text{ with } \chi^2 \approx 1.7. \]  

This suggests that a split based on axial ratio produces cleaner subsamples. It also shows that measurement errors on optical PA are not strongly biasing our results since the stronger correlation is seen for the more circular galaxies. It is interesting that splitting by axial ratio seems to separate two populations amongst these predominantly elliptical galaxies, one with \( \Delta \alpha = 90^\circ \) and the other with \( \Delta \alpha = 0^\circ \). We explore this further below when we also split the population in terms of their radio loudness.

Following Ivezić et al. (2002), it is convenient to define an AB radio magnitude in terms of the integrated flux density
\[ t = -2.5 \log_{10} \left( \frac{S_{363M}}{3631Jy} \right), \]  
and the parameter \( t - r \) then quantifies whether the galaxy is relatively radio loud or radio quiet. To put the degree of radio loudness in context, we calculate that \( t - r \approx -7 \) corresponds to an \( L^* \) galaxy having a radio luminosity which would put it roughly at the dividing line between radio sources having FR1 and FR2 radio structures (Ledlow & Owen 1996). Though the galaxies in our sample have a range of optical luminosities, the vast majority will have radio luminosities below the FR1/FR2 division. We note that since the beam size of FIRST is only 5 arcsec, the measured radio flux density will be that associated with the nuclear region and will sometimes be an underestimate of the total flux density. This fact should be borne in mind when interpreting the results presented here. It also should be made clear that our radio-quiet/loud division used later in this paper at \( t - r = -2.5 \) is different from the standard definition in two ways; we do not use the total radio flux density and, more importantly, we take the ratio of the radio emission to the total optical starlight and not the AGN light. \(^2\) In Fig. 8, we present a scatter plot of the \( t - r \) versus \( C_2 \) which appears to have an interesting morphology. One can clearly see that there are two populations separated by \( C_2 = 3.5 \). The population with \( C_2 < 3.5 \) has \( -2.5 < t - r < 1.0 \), whereas

\(^2\) Coincidently, the numerical value for the separation between our radio-loud and radio-quiet populations is the same as that usually adopted to separate radio-loud and radio-quiet quasars (Kellermann et al. 1994).
that with $C_2 > 3.5$ extends over a much wider range $-4.5 < t - r < -1.5$.

In Fig. 9, we have split the subsample with $C_2 > 3.5$ based on both $b/a$ and $t - r$. For $b/a > 0.6$ and $t - r > -2.5$ (radio quiet; bottom-left panel), there are 3441 galaxies. Their histogram is biased towards $\Delta \alpha = 90^\circ$ with $\chi^2 \approx 11$ which is the statistically strongest result we have been able to find for the correlation between major axis of the optical image and the minor axis in the radio using just photometric properties. Remarkably, for the radio-louder population with $b/a > 0.6$ the distribution of the 1805 objects is statistically indistinguishable from uniform. Thus, amongst these galaxies with $b/a > 0.6$ we appear to have isolated two populations exhibiting different behaviour depending on their degree of radio loudness. We think that the dichotomy between radio-quiet and radio-loud galaxies for $b/a > 0.6$ is an intriguing result worthy of further discussion. We will discuss this further in Section 4.

As we will explain in Section 3.4, we believe that the apparent trend towards $\Delta \alpha = 0^\circ$ in the radio-quieter subsample with $b/a < 0.6$ (top-left panel of Fig. 7) is due to contamination of the elliptical population by red star-forming galaxies. The $b/a < 0.6$ histogram for the radio-louder objects (top-right panel of Fig. 7), which contains 382 galaxies, is biased towards $\Delta \alpha = 90^\circ$, albeit with a low $\chi^2 \approx 1.6$. We deem this to be compatible with uniformity.

### 3.4 Spectroscopic identifications

In the discussion so far, we have relied on galaxy properties derived from photometric data. In addition to photometry, many of the galaxies have SDSS spectra. These data have been analysed to compute the redshift of the object, but they have also been used by a number of authors to derive a range of galaxy properties such as the stellar mass, age and star formation rate (SFR). In particular, Kauffmann et al. (2003) used SDSS spectroscopy to compute the stellar mass, $m_{\text{stellar}}$, and age, $t_{\text{stellar}}$, from two stellar absorption line ratios coupled to broad-band photometry, while Brinchmann et al. (2004) list SFRs and other parameters for SDSS galaxies using similar techniques. We note that these calculations use the DR4 catalogue whereas we have used DR6. We have used the SDSS identifiers to match up the two catalogues. For the objects we have selected, all positions in DR4 are consistent with those in DR6.

Brinchmann et al. (2004) also attempt a classification of the galaxies on the basis of their spectral lines, particularly on the location of objects in the plane defined by ratios [N II]/H$\alpha$ and [O III]/H$\beta$; that is, where objects lie in the Baldwin–Phillips–Terlevich diagram, following Baldwin, Phillips & Terlevich (1981). The galaxies are divided into four groups: star forming; active galactic nuclei (AGN); composite (i.e. have both star-forming and AGN properties) and unclassified. Before we discuss the results of our analysis using the SDSS spectroscopic data, a word of caution is appropriate; the spectra were obtained with a 3 arcsec fibre bundle and, particularly for low redshift, face-on, galaxies the spectra may be missing some star formation in discs. Some of these relatively rare objects could be labelled as unclassified (see below) because the spectroscopy only refers to a bulge of a disc galaxy.

The sample of galaxies which we have been studying contains 6053 galaxies which have entries in the tables of Kauffmann et al. (2003) and Brinchmann et al. (2004). Of these, 3752 were classified using their spectral line strengths and 2301 were not classified since they have either faint or non-existent lines. This latter sample will also be of interest to us containing, as it does, mostly early-type galaxies, a subset of the red galaxies previously selected by their photometric properties. Of the spectroscopic sample containing 6053 galaxies, 1593 were classified as star forming, 1158 as composite and 1001 as dominated by an AGN. In Fig. 10, we have split the sample according to this classification scheme. We find that the sample of star-forming and composite galaxies are significantly biased towards $\Delta \alpha = 0^\circ$ with $\chi^2 \approx 114$ and 97, respectively. The AGN are also biased towards $\Delta \alpha = 0^\circ$, but with a much lower significance ($\chi^2 \approx 3.1$). The objects which are unclassified

![Figure 9. Histograms for the case $C_2 > 3.5$ with various splits based on $b/a$ and $t - r$. The two plots at the bottom have $b/a > 0.6$ and the two at the top have $b/a < 0.6$. The two on the left are radio quiet with $t - r > -2.5$ and the two on the right are radio loud with $t - r < -2.5$.](https://academic.oup.com/mnras/article-abstract/399/4/1888/1033827)

![Figure 10. Histograms of the sample split on the basis of spectroscopic data: (bottom-left panel) all galaxies with spectroscopic data; (bottom-middle panel) those classified on the basis of spectral lines from Brinchmann et al. (2004); (bottom-right panel) those with spectroscopic data, but were not classified on the basis of spectral lines; (top-left panel) those classified as star-forming galaxies; (top-middle panel) those classified as composite; (top-right panel) those identified as AGN.](https://academic.oup.com/mnras/article-abstract/399/4/1888/1033827)
spectroscopically appear also to be biased, but this time towards $\Delta \alpha = 90^\circ$ with $\hat{\chi}^2 \approx 3.8$.

Although the numbers of objects, and hence $\hat{\chi}^2$, are lower for this spectroscopic sample, the percentage of objects in each bin for star-forming and composite galaxies is similar to that for the photometric split with $C_2 < 3.5$. Moreover, percentages for the unclassified galaxies are similar to those for $C_2 > 3.5$, indicating a close link between the spectral classification and this photometric quantity. This is confirmed in Fig. 11, where we have replotted Figs 6 and 8 but now separating spectroscopically classified galaxies and spectroscopically unclassified galaxies in the left- and right-hand plots, respectively. There are virtually no unclassified objects with $C_2 < 3.5$ (4 per cent contamination) and very few star-forming/composite galaxies with $C_2 > 3.5$ (7 per cent contamination). Furthermore, nearly all the classified galaxies, including the AGN, are radio quiet (i.e. they have $t - r > -2.5$). This reinforces our view that $C_2 > 3.5$ is a good a photometric criterion for selecting passive elliptical galaxies.

In Fig. 12, we focus on the unclassified population whose characteristic is that they have no identifiable lines in their spectra. We believe that this population consists predominantly of elliptical galaxies in which there is no evidence for current star formation nor for the presence of an active nucleus. We will term these unclassified objects as passive elliptical galaxies. Since they appear, for the most part, to have $C_2 > 3.5$ and have a bias towards $\Delta \alpha = 90^\circ$, we have attempted to improve the correlation by making splits into equal numbers above and below, i.e. equal numbers of star-forming, composite or AGN, and the histogram of their PA differences peaks at $\Delta \alpha = 0^\circ$, while there 240 which are not classified with a peak in their histogram at $\Delta \alpha = 90^\circ$. The statistical significance of the two peaks are much weaker than seen in the rest of the paper, particularly the one for the unclassified population, due to the reduced number of galaxies in the subsample. However, it seems clear that objects with $C_2 > 3.5$ and low values of $b/a$ contain a significant contamination from star-forming galaxies, composites and AGN. Visual inspection of the individual images confirms that these are indeed a population of red $(u - r \sim 3)$ spirals. In fact, 85 per cent of the galaxies which are spectral unclassified have $b/a > 0.6$ (note that we have excluded galaxies with $b/a < 0.8$ from our analysis since their PA will be affected by noise). We can therefore refine our photometric criterion to select a clean sample of passive ellipticals to include only galaxies with $C_2 > 3.5$ and $b/a > 0.6$.

The AGN population also deserves special mention. Not only is the bias towards $\Delta \alpha = 0^\circ$ much weaker than for star-forming or composite galaxies, they straddle the line $C_2 = 3.5$ with almost equal numbers above and below, i.e. equal numbers of star-forming and elliptical galaxies (see Kauffmann, Heckman & Best 2008). In Fig. 13, we present subsamples of the AGN population split using other three subsamples presented in Fig. 12 are $b/a > 0.6$ and $t - r > -2.5$, $b/a < 0.6$ and $t - r > -2.5$, $b/a < 0.6$ and $t - r > -2.5$ contain 724, 240 and 97 galaxies with $\hat{\chi}^2 \approx 1.20, 0.96$ and 1.91, respectively. All three distributions appear to have no obvious bias towards a particular angle, and at least in the first two cases are compatible with uniformity.

We briefly return to discuss Fig. 9. We see no evidence in Fig. 12 for the significant trend seen in the top-left panel of Fig. 9. The availability of spectroscopic information allows us to understand why there appears to be a significant non-uniformity for objects in this panel in terms of a mixture of star-forming galaxies and ellipticals. There are spectra for 448 galaxies with $C_2 > 3.5$, $t - r > -2.5$ and $b/a < 0.6$. 228 of these are classified as star forming, composite or AGN, and the histogram of their PA differences peaks at $\Delta \alpha = 0^\circ$, while there 240 which are not classified with a peak in their histogram at $\Delta \alpha = 90^\circ$. The statistical significance of the two peaks are much weaker than seen in the rest of the paper, particularly the one for the unclassified population, due to the reduced number of galaxies in the subsample. However, it seems clear that objects with $C_2 > 3.5$ and low values of $b/a$ contain a significant contamination from star-forming galaxies, composites and AGN. Visual inspection of the individual images confirms that these are indeed a population of red $(u - r \sim 3)$ spirals. In fact, 85 per cent of the galaxies which are spectral unclassified have $b/a > 0.6$ (note that we have excluded galaxies with $b/a < 0.8$ from our analysis since their PA will be affected by noise). We can therefore refine our photometric criterion to select a clean sample of passive ellipticals to include only galaxies with $C_2 > 3.5$ and $b/a > 0.6$.
3.5 Physical properties of the aligned galaxy populations

So far we have used the spectroscopic information to classify (or not) the galaxies as star forming, composite, AGN and unclassified. However, we have already alluded to the fact that Kauffmann et al. (2003) and Brinchmann et al. (2004) deduce \( m_{\text{stellar}} \), \( t_{\text{stellar}} \) and the SFR for a significant fraction of the galaxies we are studying. We therefore have an opportunity to investigate the connections between these inferred properties of the galaxies and the correlations we have so far found in this paper.

In Figs 14 and 15, we have plotted the fraction of the galaxies for which spectroscopy is available as a function of \( t_{\text{stellar}} \) and \( t_{\text{char}} = m_{\text{stellar}} / \text{SFR} \) for the different spectral types. The quantity \( t_{\text{char}} \) is the time which would be required for the galaxy to form all its stars at the rate they are presently being produced. Not unexpectedly, we see that there is an increase in both quantities as one goes through the spectral types from star forming, through composite and AGN, to the unclassified population. The star-forming and composite galaxies have \( t_{\text{stellar}} \sim 1-4 \text{ Gyr} \) and \( t_{\text{char}} \) typically less than the age of the Universe. The AGN population have a very broad range of \( t_{\text{stellar}} \) and \( t_{\text{char}} \), greater than the age of the Universe. The unclassified population have \( t_{\text{stellar}} > 5 \text{ Gyr} \) and a broad range of \( t_{\text{char}} \), typically \( \sim 30-300 \text{ Gyr} \). These properties are compatible with our interpretation of this unclassified population, as passive elliptical galaxies with a dominant red stellar population and with the present-day star formation either being absent or involving a very small fraction of the total stellar mass. We draw attention to the fact that the AGN appear to be less prevalent amongst the galaxies with the
smallest stellar ages, possibly suggesting that radio-loud activity tends to follow a burst of star forming rather than being coeval with it. A conclusion that activity in general (not just radio-loud activity) follows a starburst was reached by Schawinski et al. (2007) based on their study of SDSS active galaxies. A detailed discussion of the statistics of radio jets and activity in nearby galaxies is given in Kauffmann et al. (2008).

The quantities $t_{\text{stellar}}$ and $t_{\text{char}}$ can be used to help elucidate some of the properties of the interesting subsamples we have identified in the preceding sections. First, let us consider the sub-sample with $C_2 > 3.5$ and $b/a > 0.6$ which was shown to have a statistically significant correlation with $\Delta \alpha = 90^\circ$ when the galaxy is relatively radio quiet and has a uniform distribution of the PA differences when the galaxy is radio loud. For the most part, the distributions of photometrically measured and spectroscopically inferred quantities are very similar for the radio-loud/quiet sub-samples. In particular, the distributions of $b/a$ and $\Delta \alpha$ are almost identical for the two sub-samples. The most visibly different quantity is the distribution of $t_{\text{stellar}}$ versus $t_{\text{char}}$.

We have shown in Fig. 13 that the AGN population can be split using the parameter $C_2$ into a subsample which has a significant correlation towards $\Delta \alpha = 0^\circ$ ($C_2 < 3.5$) and one with an almost uniform distribution of PA differences ($C_2 > 3.5$). The properties of the stellar populations of the AGN hosts when split on the basis of $C_2$ are presented in Fig. 17. We see that the distribution of SFR is very similar for the two subsamples, but that objects with $C_2 > 3.5$ typically have a larger $m_{\text{stellar}}$ implying that the $t_{\text{char}}$ is typically larger. The sample with $C_2 < 3.5$ has $t_{\text{char}}$ sharply peaked around the age of the Universe similar to that for the composite population, whereas the distribution of $t_{\text{stellar}}$ is much broader and peaked at around 30 Gyr for $C_2 > 3.5$ more in keeping with that of the unclassified population. The distribution of $t_{\text{stellar}}$ is also interesting.

Figure 16. $t_{\text{char}}$ for galaxies with $C_2 > 3.5$ and $b/a > 0.6$, i.e. those in the bottom two panels of Fig. 9. The solid line is the radio-quiet population with $t - r > -2.5$ and the dashed line is the radio-loud population with $t - r < -2.5$.

Figure 17. Properties of the AGN population split on the basis of $C_2$: (bottom-left panel) $M_{\text{stellar}}$; (bottom-right panel) $t_{\text{stellar}}$; (top-left panel) SFR in $M_\odot$ yr$^{-1}$; (top-right panel) $t_{\text{char}}$. The solid lines are for $C_2 > 3.5$, whereas $C_2 < 3.5$ for the dashed lines.

Figure 18. Scatter plot of $t_{\text{stellar}}$ versus $C_2$ for galaxies which were identified as being dominated by an AGN. Included also is the line $C_2 = 3.5$ which has been used to split these galaxies into a subsample biased towards $\Delta \alpha = 0^\circ$ and one where the PA differences are uniformly distributed. There appears to be a strong correlation between the two quantities.

For $C_2 < 3.5$ we find that $t_{\text{stellar}}$ is typically $< 5$ Gyr whereas for $C_2 > 3.5$ it is $> 5$ Gyr.

The above results suggest that there could be a correlation between $t_{\text{stellar}}$ and the parameter $C_2$ for AGN. In Fig. 18, we plot $t_{\text{stellar}}$ against $C_2$. There is a clear correlation; there is reasonably small scatter about a line given by

$$\frac{t_{\text{stellar}}}{\text{Gyr}} \approx 0.5(8C_2 - 19).$$

(3)

There is no hint of bimodality in this distribution. It is interesting to note that star-forming and composite galaxies would typically reside in the bottom left of this diagram ($t_{\text{stellar}} < 5$ Gyr and...
$C_2 < 3.5$) whereas the unclassified population would reside in the top right ($t_{\text{stellar}} > 5$ Gyr and $C_2 > 3.5$). The PA differences for the AGN with young stellar populations appear to share the same properties as the other galaxies in that quadrant. On the other hand, the older AGN appear not to share the same properties as the other galaxies in their quadrant, though the numbers are small and the corresponding statistical uncertainties are large.

### 3.6 Intrinsic alignment between the radio and optical structures

An important question is the strength of the intrinsic alignment between the radio and optical emission both for the star-forming galaxies and the passive ellipticals. In both cases, the distributions of measured PA differences are broadened by measurement noise. The observed variance is due to the intrinsic effect ($\langle (\Delta \alpha)^2 \rangle_0$) and measurement noise ($\langle (\Delta \alpha)^2 \rangle_{\text{M}}$, which we will assume are independent and can, therefore, be added in quadrature

$$\langle (\Delta \alpha)^2 \rangle = \langle (\Delta \alpha)^2 \rangle_0 + \langle (\Delta \alpha)^2 \rangle_{\text{M}}.$$  

In what follows, we will attempt estimate the value of $\langle (\Delta \alpha)^2 \rangle_0^{1/2}$ based on a few simple assumptions. Our intention is to give an idea of the level of correlation rather than presenting a robust statistical analysis.

In addition to measurement noise, there can be projection effects. These are likely to be negligible in the case of star-forming galaxies which can be assumed to be disc-like with roughly coplanar radio and optical emission, but could be important in ellipticals which can be triaxial (Binney 1978). The possible effects of triaxiality on the observed radio/optical PA distribution were simulated by Sansom et al. (1987). Their simulations show that, for oblate spheroidal galaxies, those with jets along the minor axis should show the kind of alignments we observe, whereas other configurations lead to much less well-defined PA difference distributions; any triaxiality only serves to blur to the kind of biases we observe. An important recent contribution has been made by Padilla & Strauss (2008) who have analysed the shapes of 282 203 elliptical galaxies from SDSS. They reach the conclusion that the intrinsic shapes of ellipticals are consistent with them being oblate spheroids (with the degree of flattening increasing with decreasing luminosity). The implication of ellipticals being oblate is that projection effects should not be significant and, therefore, we will ignore them.

The measurement error, quantified by $\langle (\Delta \alpha)^2 \rangle_{\text{M}}$, can be reduced by focusing on galaxies which are bright both in the radio and in the optical and, in addition, have low-value $b/a$. However, some caution is required since it is possible that the correlation we are interested in is intrinsically connected to the value of $b/a$ (or even the optical or radio flux); for example, galaxies with low $b/a$ might have an intrinsically smaller dispersion in PA differences. We have found no evidence of this in the case where the bias is towards $\Delta \alpha = 0^\circ$ with all the results for $C_2 < 3.5$ and star-forming galaxies being compatible with measurement noise being dominant in the histograms when considered as a function of $b/a$. The situation is more complicated in the case of $C_2 > 3.5$ and passive ellipticals, where the strength of the correlation appears to improve as one increases the lower limit on $b/a$. This suggests that the true correlation is stronger than we have observed. We will assume that we can measure $\langle (\Delta \alpha)^2 \rangle_{\text{M}}$ as a function of $b/a$ for star-forming galaxies and that this holds for elliptical galaxies.

Again for objects with $C_2 < 3.5$, we have made cuts to the sample so as to get the strongest possible results in terms of the percentage of objects in each bin. We note that this is a somewhat different philosophy to that used in the rest of the paper where we have attempted to maximize the $\chi^2$. The results of this process are presented in Fig. 19. We have imposed stringent cuts of $r < 15$, in order to improve the accuracy of determination of the optical PA, and $S_{\text{min}} > 5$ mJy, to do the same for the radio PA. We will make the assumption that for $b/a < 0.5$ and $C_2 < 3.5$ the observed correlation is purely from the intrinsic scatter and that measurement errors are negligible. By performing simulations with different Gaussian dispersions, and ignoring the very few outliers, we deduce that the dispersion seen in the case where $b/a < 0.5$ is compatible with a standard deviation of $\langle (\Delta \alpha)^2 \rangle_0^{1/2} \approx 15^\circ$. This is a conservative approach since by not explicitly taking into account any radio PA measurement errors any intrinsic spread we deduce will be an over estimate of the true value. Although the existence of a correlation between the radio and optical PA in these systems may not be unexpected, the fact that it is so strong is possibly a little more surprising.

Again for objects with $C_2 < 3.5$, we now consider the correlations when $b/a > 0.6$ (which is presented Fig. 19) and $b/a > 0.7$. We find that the histogram with $b/a > 0.6$ is compatible with a total dispersion of $\langle (\Delta \alpha)^2 \rangle_0^{1/2} \approx 30^\circ$, and for $b/a > 0.7$ it is compatible with $\approx 40^\circ$. Assuming that these galaxies are from the same parent population as those with $b/a < 0.5$ – i.e. they have the same intrinsic scatter – and that the intrinsic effect is uncorrelated with the effect of the axial ratio – i.e. they can be added in quadrature – we can deduce $\langle (\Delta \alpha)^2 \rangle_{\text{M}}^{1/2}$. We find that it to be $\approx 25^\circ$ for $b/a > 0.6$ and $\approx 37^\circ$ for $b/a > 0.7$.

For the $C_2 > 3.5$ population, essentially the passive ellipticals, we have already shown that the correlation towards $\Delta \alpha = 90^\circ$ is strengthened as $b/a$ increases. The histogram with $b/a > 0.6$ is compatible with a total dispersion of $\approx 45^\circ$. If we assume that the measurement error arising from large axial ratios is the same as in the case of $C_2 < 3.5$ then one can deduce that the combination of the intrinsic effect $\langle (\Delta \alpha)^2 \rangle_0^{1/2}$, and any residual effect due to
projection, is $\approx 37^\circ$. For $b/a > 0.7$, the histogram is compatible with a total dispersion of $\approx 40^\circ$ and therefore one can deduce that the intrinsic plus residual projection effects (assumed small if they are oblate spheroids) give a dispersion of $\approx 15^\circ$. This is a surprisingly small value, especially given that previous investigations, albeit with much smaller numbers (e.g. Sansom et al. 1987), failed to produce a statistically significant result. Physically, the likely implication of such a small dispersion is that we are dealing with well-ordered systems in which the overall shape of the host galaxy dictates the nuclear accretion axis and thus the spin axis of the central black hole. The fact that the intrinsic dispersion appears to be smaller in the more circular systems is again unexpected.

4 DISCUSSION

In the previous section, we have identified and refined two correlations between the optical and radio PA; one is between the two major axes ($\Delta \alpha = 0^\circ$) and the other is between the major and minor axes ($\Delta \alpha = 90^\circ$). In the simplest terms star-forming, predominantly spiral, galaxies have $\Delta \alpha = 0^\circ$ and passive ellipticals have a bias towards $\Delta \alpha = 90^\circ$. We have tried to refine the division between objects displaying the different types of behaviour, and in Tables 1 and 2 we present a summary of the various cuts made on the data based on photometric and spectroscopic properties, respectively. We find that a new composite parameter $C_2 = 0.262c + 0.965(a - r)$ can be used to discriminate better between different populations, with most objects with $C_2 < 3.5$ having identifiable emission lines in their spectra, and those with $C_2 > 3.5$ typically being passive ellipticals with no identifiable lines. Use of the $C_2$ parameter improves the statistical significance of the PA difference separation. The propensity to select passive ellipticals can be increased by additionally requiring that $b/a > 0.6$. Interestingly, galaxies identified as being dominated by an AGN appear to straddle the line $C_2 = 3.5$. In these, as in the galaxy population as a whole, AGN with younger stellar populations and those with low axial ratios have $\Delta \alpha = 0^\circ$, whereas those with older stars which are also more circular have a uniform distribution of PA differences.

There is an obvious interpretation for the very strong bias towards $\Delta \alpha = 0^\circ$ in the galaxy population as a whole which is that it arises from the subset of all galaxies in which there is significant star formation and where the radio emission comes, either directly or indirectly, from supernova remnants associated with the evolution of recently formed massive stars. There is little direct evidence from the SDSS and FIRST data alone that the emission at the two frequencies is accurately coplanar but one should note that the resolution of the radio images is a factor of $\sim 4$ worse than that of the optical images. Also, single colour optical images are a relatively inefficient way of distinguishing regions of active star formation from the general stellar population. Hence, there is clearly scope for 1 arcsec resolution radio mapping and more detailed optical/infrared imaging of selected SDSS objects to investigate in detail the correspondence between radio and optical emission. Patel et al. (2009) are investigating in detail the shapes of high-redshift star-forming galaxies and their associated emission using Hubble Deep Field data together with high-resolution Very Large Telescope (VLA)/Multi-Element Radio-Linked Interferometer Network observations.

The bias towards $\Delta \alpha = 90^\circ$ in the red, objects with high concentrations is less strong but still highly statistically significant. Since in these predominantly elliptical galaxies the emission is almost certainly powered by mass accretion on to a central disc/black hole system, the radio elongation we measure will be related to the overall spin axis of that system. Our results confirm those reported by Condon et al. (1991) who saw a strong trend for the jet axes in elliptical galaxies found in the Uppsala General Catalogue to be aligned with the optical minor axes. Simulations done by Sansom et al. (1987) for different galaxy geometries show that one only gets the kind of strong minor axis alignments that we observe for galaxies which are oblate spheroids. We therefore interpret our results as implying that there is a bias for the spin axis of the central engine to be aligned with the minor axes of galaxies and also that these galaxies are predominantly oblate spheroids. That elliptical galaxies are oblate spheroids is consistent with the conclusions of Padilla & Strauss (2008) based on an analysis of galaxy shapes. The radio minor axis alignment is something one might expect to see if the galaxies were rotationally supported and the black hole accretion disc axes were aligned with the overall galaxy rotation axes. One should contrast what we see here in elliptical galaxies with what seems to be a much more complex situation that appears to be common in Seyfert galaxies where there is only a weak relationship between jet axis and the axis of host galaxy disc (Kinney et al. 2000; Gallimore et al. 2006; Raban et al. 2009).

The most remarkable thing that we find about the $\Delta \alpha = 90^\circ$ bias in the elliptical galaxies is the fact that strong alignment only seems to be present in the radio-quieter subset of these objects. We emphasize that we have not tried to optimize our dividing line in radio loudness to maximize the discrimination between the PA properties. The division at $t - r = -2.5$ separates the samples into subsamples with a ratio in numbers of around 2:1. The possibility that there is a priori to have any particular physical significance for the elliptical galaxy population. However, our results suggest the division does

Table 1. Summary of the splits made on the data on the basis of the spectroscopic properties.

| Split | $N$ | $\chi^2$ | Bias Fig. |
|-------|-----|---------|-----------|
| All   | 14302 | 117 | $0^\circ$ | 4 |
| $u - r < 3$ | 8933 | 212 | $0^\circ$ | 5 |
| $u - r > 3$ | 5569 | 3.6 | $90^\circ$ | 5 |
| $c < 3$ | 8803 | 215 | $0^\circ$ | 5 |
| $c > 3$ | 5499 | 2 | $90^\circ$ | 5 |
| $C_2 < 3.5$ | 7573 | 260 | $0^\circ$ | 7 |
| $C_2 > 3.5$ | 6729 | 5 | $90^\circ$ | 7 |
| $C_2 > 3.5, b/a < 0.6$ | 1483 | 1.7 | $0^\circ$ | 7 |
| $C_2 > 3.5, b/a > 0.6$ | 5246 | 7 | $90^\circ$ | 7 |
| $C_2 > 3.5, b/a > 0.6, t - r < -2.5$ | 3441 | 11 | $90^\circ$ | 9 |
| $C_2 > 3.5, b/a > 0.6, t - r < -2.5$ | 1805 | <1 | – | 9 |
| $C_2 > 3.5, b/a < 0.6, t - r < -2.5$ | 1101 | 3.8 | $0^\circ$ | 9 |
| $C_2 > 3.5, b/a < 0.6, t - r < -2.5$ | 382 | 1.6 | – | 9 |

Note. $N$ is the number of objects satisfying the criteria and $\chi^2$ is the $\chi^2$ per degree of freedom when compared to a uniform distribution.

Table 2. Summary of the splits of the data based on the classification using emission lines. Corresponding histograms are presented in Fig. 10. We used the same notation as in Table 1.

| Split | $N$ | $\chi^2$ | Bias |
|-------|-----|---------|------|
| All   | 6053 | 56 | $0^\circ$ |
| Classified | 3752 | 114 | $0^\circ$ |
| Unclassified | 2301 | 3.8 | $90^\circ$ |
| Star-forming | 1593 | 97 | $0^\circ$ |
| Composite | 1158 | 39 | $0^\circ$ |
| AGN   | 1001 | 3.1 | $0^\circ$ |
have some physical significance and is consistent with there being two types of object within elliptical population exhibiting quite different behaviour. We reiterate that the two radio populations we talk about here have nothing to do with the traditional FR1/FR2 radio morphological division between that occurs at around $t - r = -7$ not $t - r = -2.5$.

Based mainly on optical morphological and kinematic data, it has been convincingly argued that there are indeed two subpopulations of elliptical galaxies: there are those that are fairly round, are slowly rotating and are generally massive, and those with more elliptical isophotes, are fast rotating and are generally less massive (see Emsellem et al. 2007). These distinctions also appear to be related to whether or not the galaxy has a core (see Faber et al. 1997; Kormendy et al. 2009 and references therein for a comprehensive discussion of elliptical galaxy properties). What we have found by including radio PA information suggests that such a split may be evident down to the scale of the central black hole. In radio-loud objects, alignment of the central engine appears to be independent of the overall shape of the host galaxy, while in the radio-quiet population the engine knows about the galaxy shape. The degree of radio loudness is known to be a strong function of galaxy mass (Best et al. 2005), and the more massive galaxies tend to be of the non-rotationally supported type. Thus, it is very tempting to suggest a simple picture in which the radio-quieter objects are predominantly rotationally supported with matter on all scales sharing a common rotation axis, while the louder ones are not rotationally supported and have the complex kinematics often present in the rounder and most massive galaxies (Emsellem et al. 2007). However, the fact that amongst the radio-quieter population we see a stronger minor axis alignment in the rounder galaxies does not have a natural explanation. Putting this caveat aside, in the above picture having complex kinematics, perhaps even a decoupled core, results in a more efficient radio-jet producing engine, but one that can point in any direction with respect to large-scale shape of the host galaxy.

To investigate the radio-quiet/radio-loud dichotomy further, we have looked for other differences in measured and inferred properties of the two groups using the data from Kauffmann et al. (2003) and Brinchmann et al. (2004). The only significant differences we can find are that median values of the stellar mass and $t_{\text{stellar}}$ are a factor of $\sim 2$ lower in the radio-quiet population. These two quantities are not independent since the SFRs in the two types of galaxies are approximately the same and $t_{\text{stellar}}$ is the ratio of the stellar mass to $t_{\text{stellar}}$. Since it is known that the fraction of galaxies having radio luminosities above some given limit increases rapidly with increasing host galaxy stellar mass (Best et al. 2005), the smaller average stellar mass for the radio-quiet galaxies is only to be expected. We have looked explicitly to see if the degree of alignment we see depends on optical luminosity (or stellar mass) and find that there is no obvious dependence. It is noteworthy that the lower characteristic age for the stars amongst the radio-quiet population argues for a more abundant supply of gas from stellar mass loss in these, and this only serves to emphasize the point that the efficiency with which the hot gas available from the whole galaxy is converted into radio emission must be significantly higher in the radio-loud objects. Of course, cold gas can be accreted too (see Kauffmann et al. 2008) but, being passive elliptical galaxies, we expect objects in our sample to be in the regime described by Kauffmann & Heckman (2008) in which accretion is limited by the supply of hot gas from evolved stars. Thus, the physical origin of apparent dichotomy remains a mystery but is probably related in some way to the formation history of the galaxies since the effect we observe depends on both the large-scale and small-scale structure. In turn, this could be related to the environment in which the galaxy has evolved. For example, the radio-loud objects could live in dense environments around groups and clusters, whereas the radio-quiet objects could live in more quiescent environments. This issue is presently under investigation (Battye et al., in preparation). An alternative hypothesis could be that the intrinsic shape of the radio-loud galaxies is not oblate and hence projection effects hide any intrinsic correlation which might exist.

The behaviour of the AGN population is also interesting. Galaxies hosting active nuclei span the full range of galaxy types. Active galaxies with young stellar populations have the radio and optical axes aligned, albeit somewhat more weakly than in the case of star-forming galaxies. This suggests that in these the radio emission is dominated by that from supernova remnants which are correlated with starlight. The situation is less clear for galaxies with an older stellar population hosting an AGN. These AGN appear to share nearly all of the properties of the spectral unclassified population indicating that they are in all other respects passive ellipticals. However, there is no statistically significant trend for their radio emission to be aligned with the host galaxy minor axis (Fig. 13), the trend we see in the elliptical population as a whole. Perhaps this is because of the relatively small numbers involved.

On the basis of the apparent correlation between $t_{\text{stellar}}$ and $C_2$ for AGN and the absence of any kind of bimodality in Fig. 18, it might be tempting to suggest that there could be an evolutionary track from the blue-extended region to the red-compact region, as opposed to two separate populations, and that AGN possibly represent disc galaxies in the process of turning into passive ellipticals. Such a conclusion is supported by the work of Schawinski et al. (2007). However, we think that this is probably an oversimplification since the time-scale for the activity is likely to be much shorter than that required to affect the transition from a disc-dominated system into an elliptical.

There is one simple but quite significant consequence following from the fact that we identify two different alignment behaviours in the general elliptical galaxy population. It argues for the radio emission that we observe being quiescent over long time-scales. It can be seen from Fig. 11 that a range of $t - r$ of 5 (a factor of 100 in flux density ratio) encompasses virtually all the objects in the unclassified population. Thus, it would require variability of no more than an order of magnitude to blur the distinction between the alignment properties of the radio-quiet and radio-loud objects out of existence. Plausible time-scales on which aligned objects might be transformed into a misaligned one are difficult to assess but probably likely to be greater than the dynamical time-scale, perhaps a few times $10^8$ yr. Stability of the radio luminosity on this kind of time-scale would argue for a stable source of fueling, most likely mass loss from the stellar population consistent with the conclusion recently presented by Kauffmann & Heckman (2008).

Finally, an original motivation for this study was to investigate what might be found when very deep radio surveys are made with, for example, the SKA in order to detect weak lensing. Such studies are of interest because optical measurements may be susceptible to a range of systematic effects. Chang et al. (2004) have detected cosmic shear using the FIRST survey and claim that, in principle, the radio should be less affected by systematics. More conservatively, whatever they may be, the systematics are likely to be different and hence uncorrelated. Therefore, correlating the signal between the two wavebands will provide a cleaner result. Our results suggest that the radio direction of elongation of galaxies found in the very deep surveys required for weak lensing studies will be the same as the optical with a dispersion of $\sim 15^\circ$. 

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5 CONCLUSIONS

The results we have presented show that consideration of the relationship between the optical and radio PA can lead to a number of interesting inferences. The power of these results has been significantly enhanced by the rich and varied astronomical information available from the SDSS. We believe that our analysis introduces a new slant on the very significant knowledge of galaxy evolution which has already come from the SDSS. We have shown that galaxies with young stellar populations which are forming stars at a significant rate predictably have aligned optical and radio axes with a dispersion of around 15°. Much fainter versions of such star-forming galaxies will be useful for future weak lensing studies and should complement optical studies of the same fields.

Perhaps more surprisingly we have found a correlation between the radio major axis and the optical minor axis in radio-quiet passive ellipticals which, once we take into account the range of noise and projection effects related to the orientation, have a similarly low dispersion to that seen in the star-forming galaxies. Such a correlation has been long sought (e.g. Mackay 1971) because of its potential to tell us about the intrinsic shapes of the galaxies and the relationship between distribution of stars and the engine that generates the radio jets. Our results argue strongly in favour of there being a population of oblate spheroidal galaxies with radio jets aligned with the stellar minor axes. We find, in fact, evidence for two populations of passive ellipticals. Those which are relatively radio quiet show strong radio alignment with the optical minor axis while the radio-louder population has no apparent correlation between the optical and radio emission. We tentatively identify our two populations with those independently found from optical photometric and kinematic studies of ellipticals, the rounder non-rotating and massive galaxies and the more discy, rotating and less massive ones. The rotationally supported discy galaxies will naturally be oblate and have a single well-defined axis. On the other hand, the slowly rotating galaxies may have complex kinematics with the jet axes misaligned with the main stellar distribution. Jets may be bent as they propagate and triaxiality will give rise to projection effects. All this can go some way towards explaining the lack of radio/optical alignments in the radio-louder population. There is clearly great scope for further detailed optical and radio observations of these relatively radio-weak elliptical galaxies.

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