



Alignment of radio galaxy axes using FIRST catalogue

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ABSTRACT

We study the alignment of radio galaxy axes using the FIRST catalogue. We impose several cuts in order to select the candidates that are most likely to be free of systematic bias. In our study, we primarily focus on testing for alignment among sources within a certain angular separation from one another since for most sources redshift information is not available. We find a very significant effect for angular distances less than 1° . The distance scale of alignment is found to be roughly 28 Mpc, in agreement with earlier estimates, assuming that these sources are dominantly at redshift of 0.8. However, we are not able to entirely rule out the possibility of systematic bias in data. We also perform a full three-dimensional analysis using a smaller data sample for which redshift information is available. In this case, we only find a very weak signal at much larger distances.

Key words: galaxies: active – galaxies: magnetic fields – radio continuum: galaxies.

1 INTRODUCTION

There exist several observations that indicate a correlation between structures at large distance scales. For example, the quasar polarizations at optical frequencies show alignment with one another at very large distance scales, of order Gpc (Hutsemékers 1998; Hutsemékers & Lamy 2001; Jain, Narain & Sarala 2004; Hutsemékers et al. 2005). The alignment effect is seen to be particularly strong in the direction of the Virgo supercluster (Hutsemékers 1998; Hutsemékers & Lamy 2001). A similar phenomenon has also been observed in the case of radio polarizations from distant sources. In this case the correlation was seen on a smaller scale of about 100 Mpc (Tiwari & Jain 2013; Pelgrims & Hutsemékers 2015; Tiwari & Jain 2016). Furthermore, radio jets from distant galaxies were found to be aligned on a distance scales greater than 20 Mpc (Taylor & Jagannathan 2016). The signal has been further tested by Contigiani et al. (2017). This paper uses the Radio Galaxy Zoo data and finds a significant signal at small distance scales in the range [19,38] Mpc h_{70}^{-1} . Blinov et al. (2020) use Very Large Baseline Interferometry (VLBI) maps from Astrogro data base and do not find a significant signal at distance scales larger than 60.5 Mpc, which is consistent with the results obtained earlier. We point out that the radio polarizations and jet axis are in general correlated with one another, although at some relatively high frequencies this correlation is absent (Tiwari & Jain 2019; Blinov et al. 2020). Hence, excluding some high-frequency observations, we expect that if either one of these show the alignment effect, it should be present in the other observable also. The effect in both optical and radio data needs to be tested further in order to confirm its presence. Ideally there should be a dedicated study for this purpose so that the systematic effects can be controlled effectively.

Theoretically, there have been large number of proposals aimed at explaining the alignment effect both at optical and at radio

frequencies. Some of these are based on intrinsic properties of the galaxies and other invoke propagation effects. The radio alignment, which is seen dominantly at small distance scales (Tiwari & Jain 2013; Pelgrims & Hutsemékers 2015; Taylor & Jagannathan 2016; Contigiani et al. 2017), may be explained by invoking correlated magnetic fields within a cluster of galaxies (Tiwari & Jain 2016). If this is indeed applicable then it will also most likely imply alignment of optical polarizations at such scales; however, a detailed study of such a connection has so far not been done. The observed optical alignment is seen on much larger distance scales (Hutsemékers et al. 2014) and may be explained theoretically by invoking hypothetical light pseudoscalar particles (Jain, Panda & Sarala 2002; Piotrovich, Gnedin & Natsvlishvili 2009; Agarwal, Kamal & Jain 2011; Agarwal et al. 2012), vector perturbations (Morales & Saez 2007), dark energy coupled to magnetic field (Urban & Zhitnitsky 2010), cosmic strings (Hackmann et al. 2010; Poltis & Stojkovic 2010), anisotropic expansion (Ciarcelluti 2012) and a superhorizon mode in the Universe (Chakrabarty 2016). Many of these effects, such as the mixing of electromagnetic waves with hypothetical pseudoscalars (Jain et al. 2002; Piotrovich et al. 2009; Agarwal et al. 2011; Agarwal et al. 2012), are frequency dependent and would not apply at radio frequencies. The recent observation of alignment of galaxies within poor clusters (Tovmassian & Torres-Papaqui 2020) is consistent with the theoretical model proposed in Tiwari & Jain (2016). The alignment arises due to the cosmological magnetic field which may originate in the early Universe (Turner & Widrow 1988; Ratra 1992; Dolgov 1993; Gasperini, Giovannini & Veneziano 1995; Subramanian 2016). As the sources evolve and interact with field galaxies, the alignment may disappear (Tovmassian & Torres-Papaqui 2020).

In the current paper, we study the alignment of source position angles (PAs) using the VLA FIRST catalogue (Becker, White & Helfand 1995; White et al. 1997; Helfand, White & Becker 2015). The basic idea is to test if the axes of different sources within a certain angular distance are aligned with one another. The FIRST (Faint Images of the Radio Sky at Twenty-one cm) survey is a large area

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sky survey covering about 80 percent of the North galactic cap and 20 percent of the south galactic cap. The total sky area is about 10 000 deg². The survey has evolved from its first catalogue (Becker et al. 1995) to the latest catalogue released in 2014 (Helfand et al. 2015). It uses images centred at frequencies 1365 and 1435 MHz. Over most of the area the threshold of detection is 1 mJy. By design, the FIRST survey area overlaps with that of the Sloan Digital Sky Survey (SDSS) and roughly 40 per cent of the sources have optical counterparts. The data are processed and self-calibrated by an automated pipeline. The redshifts of sources are not available but the median redshift is known to be about 0.8 (Condon 1989). Although there is significant overlap with SDSS, due to the high redshifts of radio sources it is difficult to get a significant population of sources even with photometric redshifts. Hence, we shall restrict most of our study to alignment of sources within a certain angular separation. We also obtain redshifts of as many sources as possible using the catalogue compiled by Kimball & Ivezić (2008). This catalogue contains radio sources from four radio surveys, i.e. FIRST, NVSS, WENSS, and GB6 with their redshifts obtained from the optical SDSS survey. For these sources, we perform a full three-dimensional analysis. However, the number of sources in this study as well as their redshift range is limited and should be repeated with a larger sample.

Due to the large sky coverage and considerable overlap with optical survey, the FIRST catalogue is well suited for our study. It has a high density of sources which allows test of alignment at small angular scales. This would allow us to further study the alignment effect seen in radio polarizations (Tiwari & Jain 2013; Pelgrims & Hutsemékers 2015; Tiwari & Jain 2016) and radio axes (Taylor & Jagannathan 2016). We should point out that our study is somewhat different from that performed in Taylor & Jagannathan (2016). Here, we shall focus primarily on the PAs of individual sources. In contrast, Taylor & Jagannathan (2016) study the alignment among axes joining two lobes of a radio galaxy. The latter study can also be conducted using the FIRST catalogue but we postpone it to future research. The FIRST catalogue also has wide sky coverage and hence allows a test at large angular scales in order to determine if an alignment effect at distance scales seen in optical frequencies (Hutsemékers 1998; Hutsemékers & Lamy 2001; Jain et al. 2004; Hutsemékers et al. 2005) is also present in radio. However, the latter test is best performed in three dimensions. Here, we undertake this study with a limited data set for which redshifts are available through the SDSS survey (Kimball & Ivezić 2008). As mentioned earlier, this study should be repeated in future once more detailed redshift information becomes available.

The FIRST survey has also been used in an earlier study (Contigiani et al. 2017). However, our sample selection is considerably different. We rely entirely on the FIRST survey whereas Contigiani et al. (2017) uses the Radio Galaxy Zoo data. Furthermore, we impose a limit of minor axes b_{\min} such that $b_{\min} > 7$ arcsec on our data sample, whereas Contigiani et al. (2017) impose $b_{\min} > 2$ arcsec. As we discuss below, some of the other cuts also differ from ours. We find that our results differ from them in detail but qualitatively we find agreement.

2 DATA

The FIRST data set contains a total of 946 432 sources (Becker et al. 1995; White et al. 1997; Helfand et al. 2015). A large number of sources are very close to one another. These are likely to be lobes of the same radio galaxy. Including such sources will lead to spurious signal of alignment since lobes of the same galaxy are likely to be aligned with one another. We remove these sources by eliminating all sources within 1 arcmin of one another. With this cut

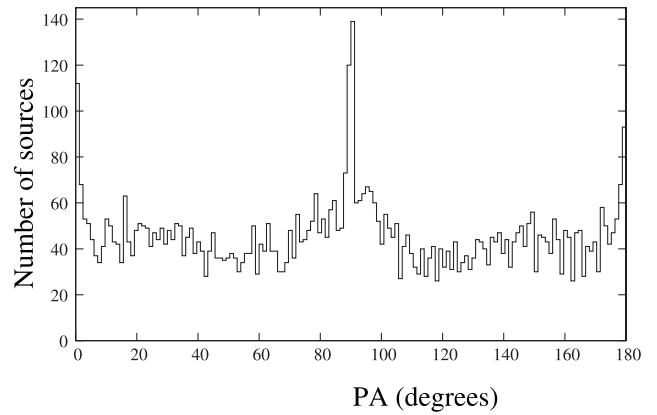


Figure 1. The histogram of PAs after removing all sources with $b_{\min} \leq 7$ arcsec, along with other cuts (source angular separation greater than 1 arcmin and Dec. $> 4^{\circ}6$) described in text.

we select only those sources which do not have any other source within 1 arcmin of itself. After imposing this cut we obtain a total of 666 021 sources. In Contigiani et al. (2017), such sources, which are very close to one other, are handled by passing a line through the sources and the slope of the resulting line is taken as the PA. We also remove all sources for which the minor axis (b_{\min}), obtained after deconvolution in the catalogue, is smaller than 7 arcsec. This is imposed since the beam itself is about 5.4 arcsec full width at half-maximum (FWHM) in the Northern hemisphere and a small beam asymmetry may introduce a bias in the PA. This cut eliminates a very large number of the sources, with only 8893 sources remaining after this cut. In the Southern hemisphere, declination less than $4^{\circ}33'21''$, the beam is elliptical, 6.4 arcsec \times 5.4 arcsec FWHM. We find that the sources in Southern hemisphere show a very large signal of alignment which is not consistent with the signal seen in the Northern hemisphere. This is discussed in more detail below. This alignment can be attributed to ellipticity of the beam and hence we only keep sources with Declination greater than $4^{\circ}6$. After this cut the number of sources are 6955.

The histogram of PAs of all the sources after imposing the cuts described above is shown in Fig. 1. We see that the distribution shows sharp peaks at PA = 0°, 90°, and 180°. These are spurious and arise due to sources for which the difference between major (b_{maj}) and minor axes is very small. Hence, we require that the ratio $(b_{\text{maj}} - b_{\min})/b_{\text{maj}} > 0.12$. We find that as we make this cut more stringent the spurious peaks at PA = 0°, 90°, and 180° get reduced eventually getting saturating once the ratio takes the value 0.12. This justifies our use of the precise upper limit on this ratio. The number of sources remaining after this cut, which we refer to as cut 1, are 5855. The scatter plot of sources is shown in Fig. 2. The histogram of PAs after this cut is shown in Fig. 3. We still see fluctuations in this distribution, however the sharp peaks at PA = 0°, 90°, and 180° are eliminated. We point out that for angular data there is no analogue of the central limit theorem and hence no preferred distribution, such as a normal distribution. However, in the present case we would have expected the distribution to be uniform. Instead we find a prominent peak at 90° and less prominent peaks roughly at PA = 25° and 150°. The reason for these peaks is not clear. This might indicate some large-scale correlation in data. Here, we shall not focus on this effect and our statistical test will use random samples that will preserve this distribution. Hence, the signal we test for is independent of the nature of this distribution.

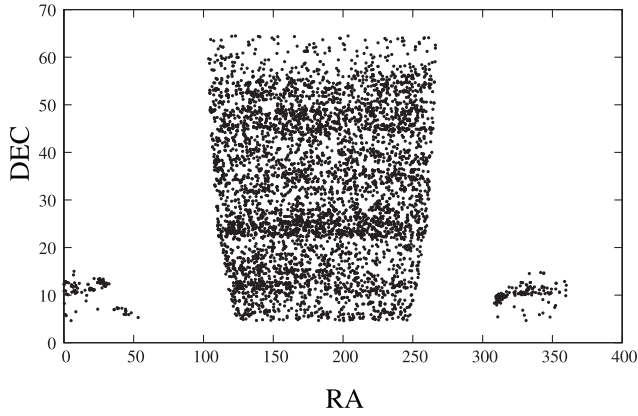


Figure 2. The scatter plot of sources after imposing cut 1.

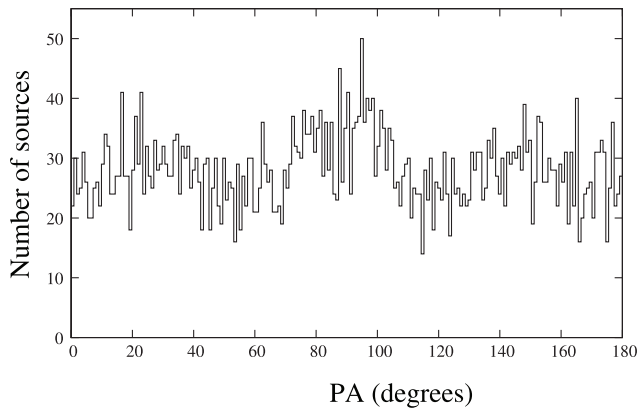


Figure 3. The histogram of PAs after imposing cut 1. This involves removing all sources with $b_{\min} \leq 7$ arcsec and $(b_{\text{maj}} - b_{\min})/b_{\text{maj}} > 0.12$, along with other cuts described in text.

The scatter plot in Fig. 2 shows that the data has some disjoint regions which contain relatively small number of sources. As discussed later, by direct calculation we find that these small regions lead to spurious results for large angular separations. Hence, it is best to remove these regions by imposing a cut $RA > 75^\circ$ and $RA < 300^\circ$. We will refer to this as cut 2 and use this data set for further studies of alignment. The number of sources remaining after this cut is 5619. The histogram of PAs with this cut remains similar to that with cut 1, shown in Fig. 3.

In the cuts imposed so far we removed all sources which are within 1 arcmin of one another. Instead of removing such sources we can also test for alignment by imposing a minimum angular separation of 1 arcmin. The analysis procedure is described in more detail below. In this case we do not need to impose the 1 arcmin cut but impose all the other cuts corresponding to cut 2. These cuts are, $b_{\min} > 7$ arcsec, $Dec. > 4^\circ 6'$, $(b_{\text{maj}} - b_{\min})/b_{\text{maj}} > 0.12$, $RA > 75^\circ$ and $RA < 300^\circ$. We refer to this as cut 3 and the total number of sources remaining after this cut are 18 775.

For our three-dimensional analysis, we use the combined catalogue (Kimball & Ivezić 2008) that uses radio data from FIRST, NVSS, WENSS, and GB6, and optical data from SDSS. After all the cuts described above, corresponding to cut 2 (or cut 3), we find a total of 593 sources which have redshift information. The redshift distribution of this set is shown in Fig. 4. We see that the distribution is sharply peaked at low z with very few sources having z greater than 0.5. Hence, it will only allow a limited test of alignment. It would

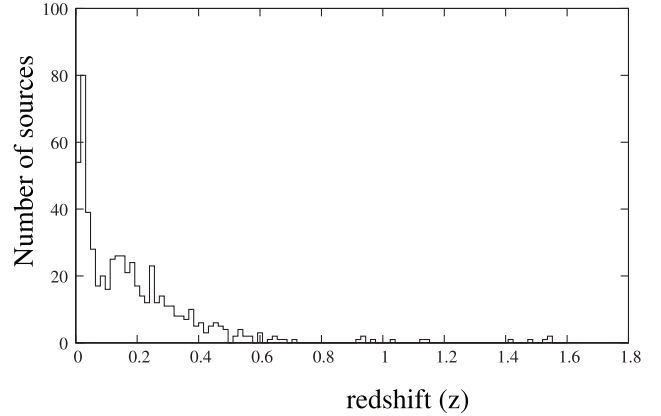


Figure 4. The histogram of redshifts after imposing cut 2. The total number of sources for which redshifts are available after imposing this cut at 593.

have been interesting to test the alignment seen in optical sources at high redshifts (Hutsemékers 1998; Hutsemékers & Lamy 2001). However, the redshift range of the present data is much smaller and hence it is not possible to reliably test the alignment on the distance scale seen in optical sources.

3 PROCEDURE

We follow the procedure outlined in Hutsemékers (1998) and Jain et al. (2004) in order to test for alignment. Let ψ_i be the PA of the i th source. For each source PA ψ_i , we define a vector \mathbf{v}_i on the surface of the celestial sphere with components $[\cos(2\psi_i), \sin(2\psi_i)]$. In order to compare these vectors for two sources i and j on the celestial sphere we need to parallel transport the vector at site i to site j . A convenient measure of alignment of two sources i and j is given by

$$d_{ij} = \cos[(2\psi_i + \Delta_{i \rightarrow j}) - 2\psi_j], \quad (1)$$

where the factor $\Delta_{i \rightarrow j}$ arises due to the parallel transport. This factor is negligible for sources at small angular separation and can be ignored in this case. However, for large angular separations it cannot be neglected.

In most of our study, we shall be testing for alignment of sources within a certain angular separation since we have limited redshift information and cannot compute the distance of most of the sources. Consider the k th source. Let there be n_k sources within an angular separation $\Delta\beta$ of this source. Here we shall include the k th source also in the n_k nearest neighbours although this will have no effect on our results. A measure of alignment of this source with other sources is given by

$$D_k(\Delta\beta) = \frac{1}{n_k} \sum_{i=1}^{n_k} d_{ik} \Big|_{\theta < \Delta\beta} \quad (2)$$

where θ is the angular separation between two sources. Let N be the total number of sources in the data set. We define the statistic

$$S_D = \frac{1}{N} \sum_{k=1}^N D_k \quad (3)$$

as a measure of alignment over the entire sample.

In order to determine the significance of the signal, we generate random samples by randomly permuting the PAs among different sources while keeping the source positions fixed. This is useful in order to preserve the distribution of PAs. We generate a large number of random samples and determine the resulting distribution of the

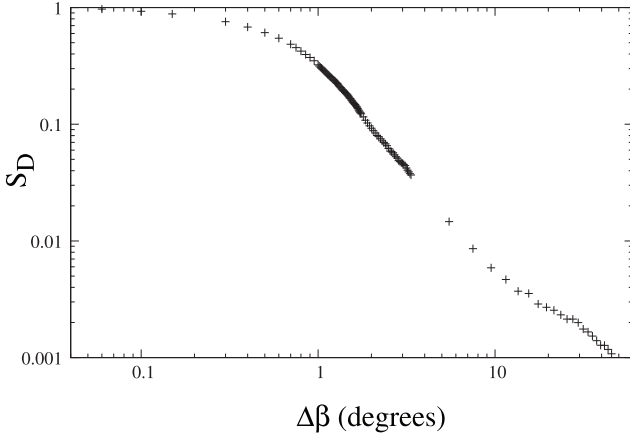


Figure 5. The statistic S_D as a function of the angular separation $\Delta\beta$.

statistic S_D that can then be compared with the data value. As we shall see the significance in many cases is found to be relatively large. So a direct numerical estimate of significance is impractical. Instead we determine the mean and standard deviation of the statistics in the random samples and use these values to compute the significance. We use 25 000 random samples for computing the significance in most cases.

It is also useful to get an alternate measure of alignment which gives an effective angular spread of PAs in data. We consider all sources within an angular separation $\Delta\beta$ of the k th. Let ψ_k^{av} be the mean angle of this set. It is obtained by maximizing the following measure A_k of alignment:

$$A_k = \frac{1}{n_k} \sum_{i=1}^{n_k} \cos [(2\psi_i + \Delta_{i \rightarrow k}) - 2\psi_k^{av}] \Big|_{\max}. \quad (4)$$

The average value A of A_k over the entire sample provides a useful measure of alignment and $\cos^{-1}A$ provides an effective measure of angular spread of $2 \times$ PAs in data. We point out that while averaging over A_k we do not include those sources that have no neighbours within the angular spread $\Delta\beta$.

The above procedure can be generalized so that we only consider sources that are at angular separation larger than a minimum value $\Delta\beta_0$ in equation (2). This is useful for the case of cut 3 in which we do not want to include sources which are within 1 arcmin of one another. We therefore generalize equation (2) as

$$D_k(\Delta\beta, \Delta\beta_0) = \frac{1}{n_k} \sum_{i=1}^{n_k} d_{ik} \Big|_{\substack{\theta < \Delta\beta \\ \theta > \Delta\beta_0}}, \quad (5)$$

where for most of our analysis we shall set $\Delta\beta_0 = 1$ arcmin. The rest of the procedure remains the same as before.

For our three-dimensional analysis, we use the statistic defined in equation (2) with the nearest neighbours selected by using the comoving distance as a measure of separation among sources. We use the Λ cold dark matter (Λ CDM) model with $\Omega_\Lambda = 0.69$ and $\Omega_M = 0.31$.

4 RESULTS

The statistic S_D for cut 2 as a function of the angular separation $\Delta\beta$ is shown in Fig. 5. The corresponding P -values, that is the probability that the statistic can arise as a random fluctuation, are shown in Fig. 6. The sigma values are also shown on this plot. We find that S_D decreases rather sharply for small values of $\Delta\beta$ and

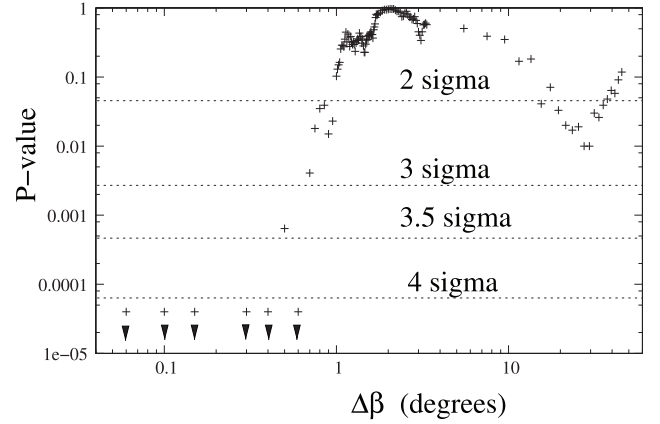


Figure 6. The probability that the statistic observed in data can arise as a random fluctuation as a function of the angular separation $\Delta\beta$. The sigma levels are indicated for convenience. We have obtained the P -values by generating a maximum of 25 000 random samples. The lower six points indicate that the P -value is smaller than $1/25\,000$.

starts to decay gently for larger values, $\Delta\beta > 10^\circ$. In Fig. 6, we see that for small values of $\Delta\beta$, less than 1° , the significance is very large (small P -values), nearly 4σ . We have computed the P -values by generating a maximum of 25 000 random samples. In some cases this did not generate even a single random sample with statistic larger than the data value. Hence, in these cases, the P -value is smaller than 4.0×10^{-5} and is indicated by downward pointing arrows in Fig. 6. We find that the significance is very large, consistently more than 4σ , for $\Delta\beta \leq 0.7^\circ$. The significance reduces with increase in $\Delta\beta$ and we do not observe a significant alignment effect for $\Delta\beta > 1.5^\circ$. For larger values of $\Delta\beta$, the P -values start to become smaller for $\Delta\beta$ in the neighbourhood of 25° and reach about 2.5σ significance level.

We point out that if did not impose the cut on declination, the statistical significance is much higher for all values of $\Delta\beta$. This indicates a clear difference between data in the Northern and the Southern hemisphere that suggests presence of a systematic effect, justifying our cut on Declination. The problem is associated with the ellipticity of the beam, as described in Section 2. Furthermore, if we did not remove the small disjoint regions by imposing the cut on RA, we find high significance for large values of $\Delta\beta$ but negligible change for small values of this variable.

We next determine how the results may change if instead of drawing the random samples from the data distribution, we drew them from a uniform distribution. For this purpose, we simply compare the mean and standard deviations of the S_D values obtained from a large number of random samples generated from the two different distributions of PA. For this test, we set $\Delta\beta = 1^\circ$. For the random samples obtained from the data distribution (Fig. 3), we obtain the mean and standard deviation to be 0.2093 and 3.6×10^{-3} , respectively. The corresponding values for a uniform distribution are found to be 0.2088 and 3.6×10^{-3} , respectively. Hence, we find negligible change for $\Delta\beta = 1^\circ$. For large angular separations ($\Delta\beta = 45^\circ$), we do find a significant difference, as expected. In case for the data distribution we find mean and standard deviation to be 5.11×10^{-4} and 1.29×10^{-4} , respectively, and for uniform distribution, 1.20×10^{-4} and 1.23×10^{-4} , respectively. The two are clearly different. We also find that for this case the data statistic value is 5.78×10^{-4} . It is clear that we do not get a significant signal of alignment if we compare this value with random samples generated from the data distribution. However, we do get a significant effect if we use a uniform distribution. A direct numerical calculation

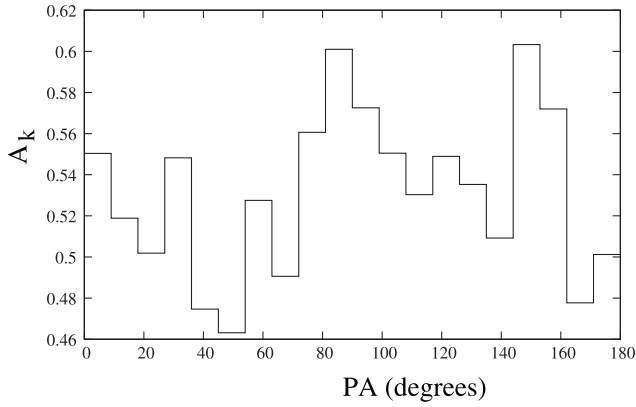


Figure 7. The binned measure of alignment A_k (equation 4) as a function of PA for $\Delta\beta = 0.6$.

shows that the significance is a little less than 3σ (P -value ≈ 0.01), although the mean and standard deviation values may suggest a higher significance. This difference arises since the distribution differs from a Gaussian for large values of the statistic. Hence, we find that although the non-uniform nature of the PA distribution in Fig. 3 suggests a large-scale correlation the effect is not very significant.

We next determine the quantity A , i.e. average value of A_k defined in equation (4). For this calculation, we set $\Delta\beta = 0.6$. This value is chosen since beyond this the significance drops significantly. We obtain $A = 0.533$. This corresponds to an angular spread $2 \times \text{PA}$ of 58° . Hence, the PAs appear to be aligned within an angular region of $\pm 29^\circ$.

We next determine which values of PAs give dominant contribution to alignment for the case of $\Delta\beta = 0.6$. In Fig. 7, we plot binned values of A_k as a function of PA. We find a peak around $\text{PA} = 85^\circ$ and another around $\text{PA} = 145^\circ$.

In Fig. 6, we see that the alignment effect is seen dominantly on angular scales of less than 0.7 . This scale is similar to the size of the co-added images. On such scales, it is possible to have alignment if there are significant beam and/or sidelobe effects present in data. In order to study this possibility, we performed two additional tests:

1. We investigate if there are any sources present in our sample for which the PA before ($\text{PA}_{\text{before}}$) and after (PA_{after}) deconvolution differs by a large amount. Such sources are likely to have significant contributions from beam asymmetry effects and can lead to a spurious signal. We specifically imposed the cut $|\text{PA}_{\text{before}} - \text{PA}_{\text{after}}| < 15^\circ$. We find that all of the sources in our sample satisfy this cut and no additional sources get eliminated.

2. We compute the error in the major and minor axes of all the sources in order to determine if the sources are well resolved. We use the following empirical formula to estimate the error σ in size (White et al. 1997):

$$\sigma = 10 \text{ arcsec} \times \left(\frac{1}{\text{SNR}} + \frac{1}{75} \right). \quad (6)$$

We find that the ratio $b_{\text{maj}}/\sigma > 4$ and $b_{\text{min}}/\sigma > 3.2$ for all the sources in our final data sample. This implies that all the sources considered in our study are well resolved.

This analysis gives us further confidence that the data sample is reliable and the signal we observe may be caused by a physical effect.

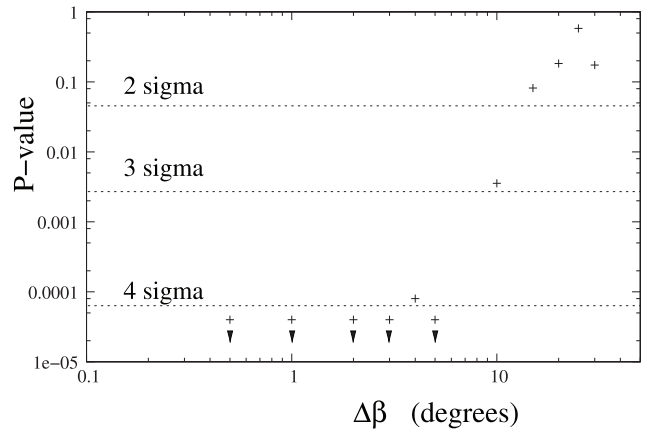


Figure 8. The P -values for the case of cut 3 as a function of the upper limit on $\Delta\beta$ with the lower limit set at 1 arcmin. The P -values are generated using 25 000 random samples. The lowest data points indicate that no random sample exceeded the data statistic.

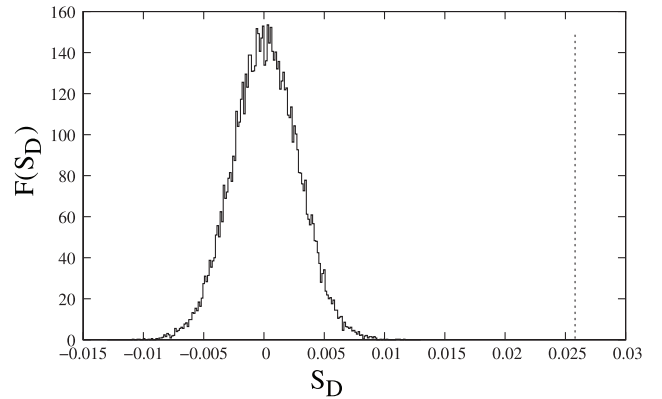


Figure 9. The normalized distribution of statistic S_D for random samples for the upper limit on $\Delta\beta = 1^\circ$. The dashed line at the right shows the data statistic.

4.1 Results with cut 3

In this case, we have a larger data sample of 18 775 sources and we test for alignment only for sources that have angular separation greater than 1 arcmin. Hence, we use equation (5) in computing our statistic. We find that this sample shows a much stronger signal of alignment for small angular separations. The results are shown in Fig. 8. We see a very strong signal of alignment up to angular separations $\Delta\beta$ of 5° . For larger angular separations, greater than 15° , we do not see a significant signal. For small separations, the signal is actually much stronger in comparison to what is indicated in Fig. 8, which is based on using 25 000 random samples. We show the distribution of S_D for the random samples in Fig. 9 along with the data statistic for the upper limit on $\Delta\beta = 1^\circ$. The mean and standard deviation of the distribution is found to be 1.3×10^{-4} and 2.72×10^{-3} , respectively. With the data statistic value of 2.58×10^{-2} , this implies a significance of 9.4σ . We find that the significance decreases monotonically as we increase the angular separation.

It is also useful to test in which range of angular separations we get significant alignment. It is very clear from our results that small separations lead to a very strong signal. However, it is possible that larger separations are only adding noise and the signal is dominantly arising from very small separations. In order to determine the regions

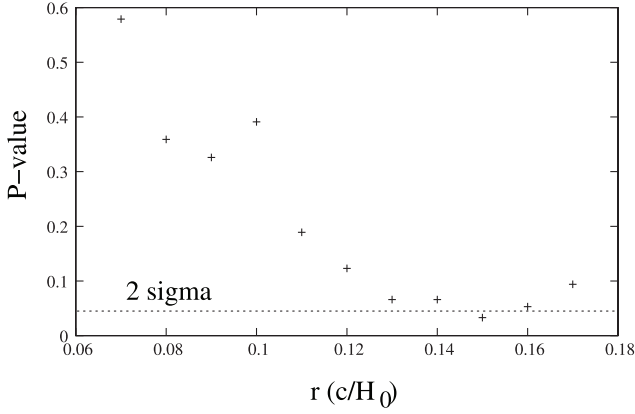


Figure 10. The probability that the statistic observed in data can arise as a random fluctuation as a function of the comoving distance r in units of c/H_0 . The 2σ levels is indicated for convenience. Here, we use the three-dimensional analysis with the cut $z \leq 0.5$.

that give significant contribution, we repeat the test of alignment in different regions. In particular, we test for the region between $\Delta\beta_0 = 0.75$ and $\Delta\beta = 1.25$. We find that in this region the significance of alignment is approximately 2.5σ and hence is not negligible. For angular intervals centred at larger values the $\Delta\beta$ the significance drops considerably. Hence, we conclude that the alignment is present only on angular scales up to about 1° .

Finally, we determine the distance scale of alignment within the Λ CDM model. The dominant signal of alignment is seen up to angular distance of 1.0° s. The sources in this catalogue peak at the redshift (z) of about 0.8. Assuming this value we can determine the distance scale of separation corresponding to 1° angular separation at $z = 0.8$ using Λ CDM model with $\Omega_\Lambda = 0.69$, $\Omega_M = 0.31$ and $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and spatially flat metric. The relationship between the angular diameter $\Delta\beta$ and physical length L of the object at redshift z is given by

$$L = d_A \Delta\beta, \quad (7)$$

where d_A is the angular diameter distance. This leads to a distance scale L of approximately 28 Mpc which is in agreement with earlier result on the alignment of galaxy axis (Taylor & Jagannathan 2016) but somewhat smaller than that obtained in Tiwari & Jain (2013).

4.2 Three-dimensional analysis

In this section, we present the results of the three-dimensional analysis using 593 sources for which redshifts z are available from the SDSS survey (Kimball & Ivezić 2008). In this case, we use the comoving distance r as a measure of separation. We use the Λ CDM model with $\Omega_\Lambda = 0.69$ and $\Omega_M = 0.31$ and spatially flat metric. We test for alignment over a range $r = 0.05$ to $r = 0.17$ in units of c/H_0 . For the full sample, we do not find a significant signal for any of these values. We also try a cut such that $z \leq 0.5$, which is motivated by the fact that there are very few sources with z is greater than this value. Hence, these would act as outliers. With this cut the P -values are shown in Fig. 10. We find a very mild signal for $r \approx 0.15c/H_0$ which corresponds to a distance of approximately 640 Mpc.

5 CONCLUSIONS

We have studied the alignment of radio axes using the FIRST catalogue. We impose several cuts on the data in order to select

a sample that may be free of bias arising due to asymmetric beam or due to irregular sky coverage. In most of our analysis, we restrict our work to a test of alignment among sources projected on the celestial sphere and separated within a certain maximum angle. This is because for most of these sources redshift information is not available. We also perform a full three-dimensional test for a subset of sources for which the redshift information is available. For our two-dimensional test, we found that the radio sources show a strong signal of alignment over angular scales of order 1° or smaller. This corresponds to a distance scale of 28 Mpc within Λ CDM model, consistent with earlier observations (Taylor & Jagannathan 2016). We also see a mild effect at larger angular scales of order 25° in one of our samples. Here, the significance is a little larger than 2σ . However, this effect is absent in a larger data sample and hence is likely to be a statistical fluctuation. The effect seen at smaller angular scales is consistent with what has been seen earlier. However, in order to firmly establish it we need to rule out the possibility of systematic bias in data. In our analysis, we have identified several sources of bias and imposed several cuts in order to reduce such effects. However, the possibility that the effect could arise from beam effect cannot be entirely ruled out since the dominant alignment is seen only over small angular scales. A dedicated study to extract the PAs relatively free of systematic effects is needed in order to firmly establish the result.

In our three-dimensional analysis, which uses a significantly reduced data sample, we do not find a very significant effect. In this case due to limited number of source, we are unable to test at very small distances and hence the absence of effect is consistent with our results of the two-dimensional test. After eliminating a few outliers at $z > 0.5$, we do find a very mild effect at distance scale of 640 Mpc. This may be tested further with enhanced data sample.

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DATA AVAILABILITY

No new data were generated or analysed in support of this research.

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