

The different neighbours around Type-1 and Type-2 active galactic nuclei

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One of the most intriguing open issues in galaxy evolution is the structure and evolution of active galactic nuclei (AGN) that emit intense light believed to come from an accretion disk near a super massive black hole^{1,2}. To understand the zoo of different AGN classes, it has been suggested that all AGN are the same type of object viewed from different angles³. This model—called AGN unification—has been successful in predicting, for example, the existence of hidden broad optical lines in the spectrum of many narrow-line AGN. But this model is not unchallenged⁴ and it is debatable whether more than viewing angle separates the so-called Type-1 and Type-2 AGN. Here we report the first large-scale study that finds strong differences in the galaxy neighbours to Type-1 and Type-2 AGN with data from the Sloan Digital Sky Survey (SDSS; ref. 5) Data Release 7 (DR7; ref. 6) and Galaxy Zoo^{7,8}. We find strong differences in the colour and AGN activity of the neighbours to Type-1 and Type-2 AGN and in how the fraction of AGN residing in spiral hosts changes depending on the presence or not of a neighbour. These findings suggest that an evolutionary link between the two major AGN types might exist.

Much of our understanding of the active galactic nuclei (AGN) structure relies on the AGN unification model. The model has been successful in predicting, for example, the existence of hidden broad optical lines in the spectrum of many narrow-line AGN, as well as ionization cones and the isotropy of the [O III]5007 line emission. It was developed after the detection of a hidden broad-line region (BLR) in the spectrum of a Seyfert 2 galaxy when observed in polarized light⁹. This indicated that the light from the accretion disk passes through optically thick material on the way to the observer. In the extreme simplification of Antonucci's model³, the accretion disk and BLR can be hidden from the observer's view when embedded in a doughnut-shaped dust torus. The Type-1 AGN (broad-line) are viewed face-on to the opening of the torus, whereas in Type-2 AGN (narrow-line) one faces the obscuring part of it. In a more realistic scenario, the covering factors of the tori differ for each individual AGN (ref. 10). Also tori consisting of many individual dust clouds having different covering factors have been considered¹¹. These differences in the observables prevent us from directly comparing the intrinsic properties of the two types of AGN due to mass-to-luminosity biases.

An unresolved issue has been the subject of much controversy: if the viewing angle is all that separates objects with otherwise identical AGN properties, why do only 50% of the Type-2 AGN reveal a hidden BLR (ref. 4)? Some common explanations have so far been extremely low accretion rates^{12,13} and extreme obscuration¹⁴.

So are Type-1 and Type-2 AGN truly representing the same kind of object?

The main idea of our hypothesis is that if Type-1 and Type-2 AGN are intrinsically the same objects, only viewed from different angles, their neighbours should, in a statistical sense, not differ systematically. On top of this, the AGN should interact in similar ways with them.

We construct parent samples of broad-line (Type-1) and narrow-line (Type-2) AGN at redshifts $0.03 < z < 0.2$ using optical emission line classification methods (Balmer line width and Kauffmann criteria¹⁵) based on data from SDSS DR7. This gives us in total 11,334 Type-1 and 53,416 Type-2 AGN. It is important to note that the AGN Unification does not unify radio-loud and radio-quiet AGN. However, the vast majority of AGN in spiral hosts are radio-quiet and are at these luminosities classified as Seyfert galaxies. We therefore also make use of the morphological classifications of the AGN host galaxies from Galaxy Zoo, where the hosts are classified either as 'Spiral', 'Elliptical' or 'Uncertain' based on voting percentages (at least 80%). The 'Uncertain' category includes those objects classified as neither 'Spiral' nor 'Elliptical'. We verify that the samples in volume-limited subsample cuts have qualitatively similar distributions in redshift, absolute magnitude and luminosity $L([\text{O III}]5007)$, see Supplementary Figs 1–3. Neighbours with spectroscopic redshifts are selected with the redshift difference cut $|\Delta z| < 0.012$ and within a projected distance of 350 kpc, yielding 1658 Type-1 and 5698 Type-2-galaxy pairs. The difficulties of detecting close neighbours due to spectroscopic fibre collisions causes pairs closer than 55" from each other not to be detected, unless residing in overlapping regions of the SDSS fibre plug plates. Therefore, photometric comparison samples are additionally constructed, with neighbours having photometric redshifts $|\Delta z| < 0.03$ and within a projected distance of 350 kpc. The final samples of galaxies with photometric redshift neighbours are 13,519 Type-1 and 58,743 Type-2 AGN-neighbour pairs. A cut in absolute magnitude for the neighbours (for example, $M_r < -21.2$, as is used for the volume-limited samples below) removes stars and other faint objects among the contaminants.

The details of the sample selection, various selection effects and the treatment of biases predicted from clumpy dust torus models are all discussed in the Supplementary Information.

For the AGN-galaxy pair samples we study how the $u_e - r_e$ colour ('e' here stands for 'internal extinction corrected') of the normal non-AGN neighbours behaves as a function of projected distance between the companion and the AGN. The colour of a galaxy can disclose information on the star formation, dust content, metallicity and age distribution of the stellar populations, which are

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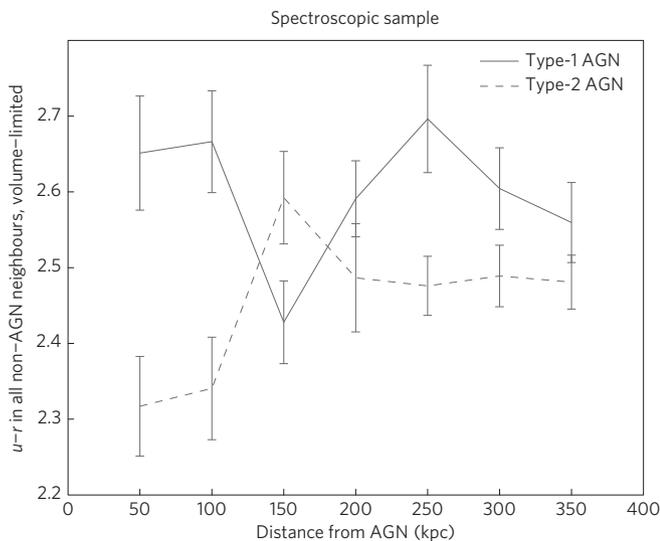


Figure 1 | Mean $u_e - r_e$ colour of inactive neighbour galaxies. The data are shown as a function of projected distance to the AGN, grouped in 50 kpc bins. The spectroscopic redshift pairs have $|\Delta z| < 0.012$ and the neighbour colours are corrected for underlying stellar absorption and internal extinction ('e' in the colour indices stands for 'internal extinction'). Volume-limited samples are used—both host galaxy and neighbour have $z < 0.14$ and $M_r < -21.2$. The number of pairs in the plot is 552 for the Type-1 AGN and 890 for the Type-2 AGN. Standard Gaussian errors for each bin are indicated by the 1σ error bars. The Type-1 AGN neighbours are redder on average than the Type-2 AGN neighbours, with 4.5σ significance. The difference in colours of the neighbours disagrees with the expectations from AGN Unification predicting the same colour of the neighbours. Changing the redshift difference cuts $|\Delta z| < 0.001$, 0.006 or 0.012 does not influence the average colours of the Type-1 and Type-2 AGN neighbours.

important physical properties for understanding galaxy evolution. Besides removing the AGN among the neighbours, all the nuclear emission-line regions (LINERs) are removed.

Figure 1 shows that the average colour of the neighbours is redder around Type-1 AGN than around Type-2 AGN, with $\sim 4.5\sigma$ significance. This finding points to systematic differences between Type-1 and Type-2 AGN not captured in AGN unification. Instead, this could mean that neighbours to Type-1 AGN are experiencing less star formation, have more dust, a higher metallicity or older stellar populations than Type-2 AGN neighbours and that Type-1 and Type-2 AGN might have formed in different environments. The analysis is redone using two more $|\Delta z|$ cuts: $|\Delta z| < 0.001$ and $|\Delta z| < 0.006$ and the results stay consistent with the previous ones.

To improve the sample statistics and include the unseen neighbours due to fibre collisions, a similar analysis is done with the larger photometric neighbour samples, see Fig. 2. The most striking feature is the very strong trend towards bluer neighbours very close to the Type-2 AGN, something that might indicate a strong increase in star formation or AGN activity in the neighbour.

It is conceivable that AGN unification is limited to some particular morphological type. In the Seyfert samples, Type-1 and Type-2 AGN hosts exhibit very similar trends to those in Fig. 2. For the elliptical hosts, there are too few Type-2 neighbours to do a similar analysis, but for the closest bin we calculated the mean value for Type-2 AGN neighbours ($u - r \sim 2.02 \pm 0.04$) and for the Type-1 AGN neighbours ($u - r \sim 2.53 \pm 0.01$).

We also try to match Type-1 and Type-2 AGN better in stellar mass and AGN activity. The AGN unification predicts $L([\text{O III}])$ to be an isotropic indicator of AGN activity that measures the strength of the isotropically distributed narrow-line region (NLR) outside the torus. This means that Type-1 and Type-2 AGN with the

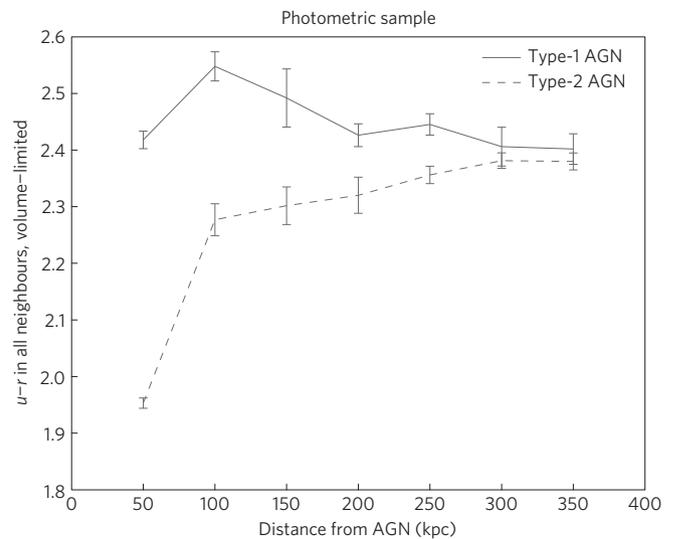


Figure 2 | Mean $u - r$ colour of neighbour galaxies. The data are shown as a function of projected distance to the AGN, grouped in 50 kpc bins. Photometric redshift pairs that have $|\Delta z| < 0.03$ are used. Both host galaxy and neighbour have $z < 0.14$ and $M_r < -21.2$ (volume-limited). The number of pairs in the plot is 1,836 for the Type-1 AGN and 3,662 for the Type-2 AGN. Standard Gaussian errors for each bin are indicated by the 1σ error bars. As no emission line information is available for these neighbours, we cannot correct them for internal extinction or remove the AGN among them. Therefore one can see that the colours are slightly bluer for these neighbours than for those in the spectroscopic pair samples. The Type-1 AGN neighbours are redder on average than the Type-2 AGN neighbours, with 20σ significance, and show no correlation in the neighbour colour over projected distance. The Type-2 AGN neighbours become much bluer at the shortest projected separation, with $\sim 24\sigma$ significance. The differences in colours of the neighbours disagree with the expectations from AGN Unification predicting the same colour of the neighbours.

same $L([\text{O III}])$ and redshift should have the same properties regarding their host galaxies (for example, mass). We construct $L([\text{O III}])$ -matched control subsamples. Starting from the photometric neighbour samples, each Type-1 AGN is one-by-one matched with the Type-2 AGN having the closest redshift and $L([\text{O III}])$. This includes also subsamples with only spiral host galaxies that are visually selected to be face-on to reduce dust extinction from the host galaxy plane. Therefore the same analysis is performed with the one-by-one matched control samples looking at colours of neighbour galaxies with the same absolute magnitude cut, $M_r < -21.2$. The results stay consistent (Supplementary Section 1.7.2).

We also calculate how the ratio between the number of Type-1/Type-2 neighbours around Type-2 AGN varies as a function of distance from the Type-2 AGN, see Fig. 3. This ratio should not depend on distance, if Type-2 AGN as central objects do not prefer one type of AGN neighbour over the other. However, we find a clear increase (with 4.5σ significance) of the ratio at large projected separations. This is consistent with the observed deficit of Type-1 AGN in isolated galaxy pairs¹⁶.

One could also wonder whether the presence of a neighbour might influence the morphology and AGN type of the host galaxy. It has been an open question whether there exists any correlation of host galaxy morphology with AGN type¹⁷. Both questions can be addressed by comparing the morphologies of Type-1 AGN and Type-2 AGN in the parent samples with those having neighbours within two different projected distances: 100 kpc and 350 kpc. This allows us to examine how the presence of a nearby neighbour (indicator of future or past interaction/merger) alters the observed

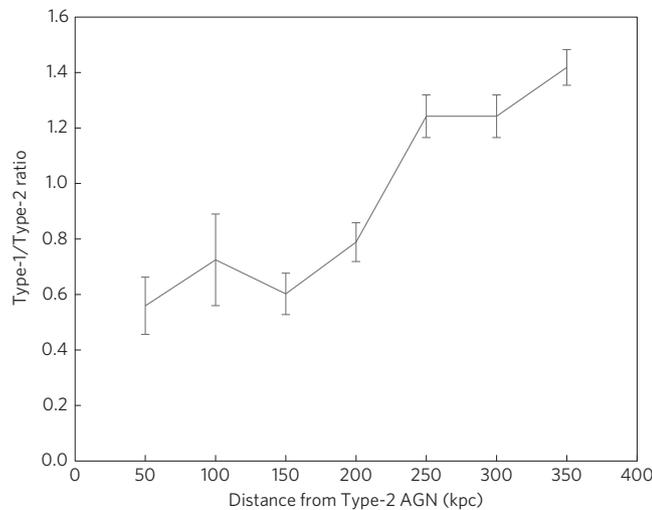


Figure 3 | Ratio in the number of Type-1/Type-2 AGN companions to Type-2 AGN. The ratio of Type-1/Type-2 AGN with spectroscopic redshifts around Type-2 AGN as a function of distance from the Type-2 AGN. LINERs are excluded and we use neighbours with $|\Delta z| < 0.012$. Including LINERs among the companions does not influence the conclusions. In total, 92 Type-1 AGN and 527 Type-2 AGN companions. The errors are Poissonian and the significance level of the trend is 4.5σ . The same trend is seen when using $|\Delta z| < 0.001$ (not shown here). In taking the ratio, many biases due to sample selection will cancel each other. The trend disagrees with the expectations from the AGN Unification predicting a horizontal line. Changing the redshift difference cuts $|\Delta z| < 0.001$, 0.006 or 0.012 does not influence the trend.

morphology of the AGN host galaxy, as mergers of gas-rich spiral galaxies of similar masses could become elliptical galaxies¹⁸.

Figure 4 shows how the fraction of AGN in spiral host galaxies depends on AGN type and the presence of a neighbour. The clustering as seen by the number of galaxies in different $|\Delta z|$ -cuts (Supplementary Table 2) suggests the two AGN types reside in similarly dense environments. We note that the number of Type-1 AGN hosts with uncertain morphologies (neither spiral or elliptical) does not change significantly in the presence of a neighbour (Supplementary Table 4). For the case of Type-2 AGN, the fraction of host galaxies with uncertain morphologies decreases from 47.3 to 38.7% with 6σ significance—the morphologies of the host galaxies get much more well defined in the presence of a neighbour. The behaviour of the host morphologies of Type-2 AGN as seen in Fig. 4 contradicts the expectations from the morphology–density relation, which predicts the fraction of spiral hosts to drop in denser environments.

The pronounced difference between Type-1 and Type-2 AGN host morphology behaviour implies one of the following three scenarios: the companion has a much smaller mass than the Type-2 AGN, favouring the formation of spiral arms in the AGN host galaxy (however, here the neighbours are fairly massive) or the Type-2 AGN do not merge with their neighbours (by some exotic mechanism) or the Type-2 AGN are fragile and are not preserved in their original state during/after merger. In the high-redshift universe when mergers were more common, the fragility would result in a deficiency of narrow-line AGN. This is indeed consistent with the observed lack of narrow-line quasars at high redshift.

So what could Type-2 AGN transform into during mergers? Elliptical Type-2 AGN might represent a form of transition object between the two types and could explain why not all narrow-line AGN show broad lines in their polarized spectra^{4,19}. We would in such a case expect to see that $\gg 50\%$ of the Type-2 ellipticals reveal a hidden BLR. This is testable by spectropolarimetric observations.

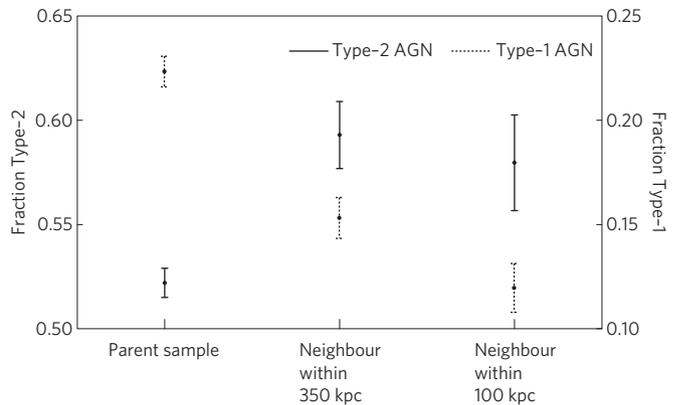


Figure 4 | The fraction of host galaxies with spiral morphology in different environments. Both host galaxy and neighbour are in volume-limited samples with $z < 0.14$ and $M_r < -21.2$. We compare three different environments: AGN in the parent samples, AGN with neighbour within 350 kpc, and AGN with at least one neighbour within 100 kpc. The errors are Poissonian. Type-1 AGN residing in spiral hosts are 22% in the parent samples and decrease to 12% having a close neighbour within 100 kpc (7.5σ statistical significance when considering the difference of the two values). For Type-2 AGN, the fraction of AGN in spiral host galaxies on the contrary increases from 52 to 58% on a 2.5σ statistical significance level (or 52 to 59% (4σ) for a neighbour within 350 kpc). This implies strong differences in how the morphology of the Type-1 and Type-2 AGN host galaxy depends on the presence of a neighbour.

Evolution of intrinsic properties such as stellar ages with redshift could help to estimate the average lifetime of the object. The Krongold–Koulouridis scenario²⁰ offers an evolutionary scenario where Type-2 AGN gradually transform into Type-1 and may agree with the decrease of the Type-1/Type-2 AGN ratio near Type-2 AGN and the increased number of blue, gas-rich neighbours near Type-2 AGN. In this scenario, the Type-2 AGN activity is initiated by the merger of two galaxies. At first, the star-formation induced by the merger will dominate the spectrum, but on relaxation of the starburst and subsequent accretion of matter, a Type-2 nucleus is formed. When the merger completes and the AGN becomes so powerful that it blows away the dust torus, a Type-1 AGN is observable. The implied timescales for such a development would, however, require the AGN activity to be highly episodic in order for the super massive black hole not to get heavier than observed.

We have demonstrated that the influence of active galaxies on close neighbours largely depends on the nature of the AGN—whether it is a broad-line or a narrow-line AGN. This is an unexpected result and shows the contrasting fates the two types of AGN face in mergers and interactions. With follow-up studies employing accurate host galaxy mass estimates, the missing links regarding the role of AGN in galaxy evolution may finally be disclosed once we accept the distinct voices the two classes of AGN have to play in the symphony of cosmic structures.

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Author contributions

Both authors contributed equally to interpreting the results and writing the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.