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 hole1,2. 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 Zoo7,8. 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 model10, 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 rates12,13 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 Kaufmann 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 viewing 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([O III]5007), see Supplementary Figs 1–3. Neighbours with spectroscopic redshifts are selected with the redshift difference cut |Δz| < 0.012 and within a projected distance of 350 kpc, yielding 1658 Type-1 and 5968 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 |Δz| < 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_r − r_s colour (c’ 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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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.

To improve the sample statistics and include the unseeded 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 neighbourhood.

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 from Type-2 AGN neighbours ($\mu - r \sim 2.02 \pm 0.04$) and for the Type-1 AGN neighbours ($\mu - r \sim 2.53 \pm 0.01$).

We also try to match Type-1 and Type-2 AGN better in stellar mass and AGN activity. The AGN unification predicts $L([\text{O} \text{III}])$ 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 same $L([\text{O} \text{III}])$ and redshift should have the same properties regarding their host galaxies (for example, mass). We construct $L([\text{O} \text{III}])$-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 $L([\text{O} \text{III}])$. 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 $4.5\sigma$ significance) of the ratio at large projected separations. This is consistent with the observed deficit of Type-1 AGN in isolated galaxy pairs.

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 type. 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
Evolution of intrinsic properties such as stellar ages with redshift could help to estimate the average lifetime of the object. The Krongold–Koulouridis scenario\textsuperscript{22} 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 whether it is a broad-line or a narrow-line AGN. This is an unexpected result and shows the contrasting fates the two types ever, require the AGN activity to be highly episodic in order for the super massive black hole not to get heavier than observed.

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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.\textsuperscript{19,41} We would in such a case expect to see that 50% of the Type-2 ellipticals reveal a hidden BALR. This is testable by spectropolarimetric observations.

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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.