Quasars are more luminous than radio galaxies – so what?

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Abstract

Surveys to find high-redshift radio galaxies deliberately exclude optically-bright objects, which may be distant radio-loud quasars. In order to properly determine the space density of supermassive black holes, the fraction of such objects missed must be determined within a quantitative framework for AGN unification. I briefly describe the receding torus model, which predicts that quasars should have more luminous ionizing continua than radio galaxies of similar radio luminosity, and present evidence to support it. I also suggest two further tests of the model which should constrain some of its parameters.

Key words: galaxies: active – radio continuum: galaxies

1 Introduction

As the cosmological applications of radio galaxies become clearer, it is important to realize that they do not represent a fundamental class of object. Searches for high-redshift radio sources use spectral index and optical magnitude selection criteria which result in the exclusion of radio-loud quasars even though these are fundamentally the same objects, according to the standard AGN unification paradigm. While this does not matter if one is using radio galaxies simply as signposts to locate and study places where large-scale structure is developing (1, 2), it is possible that they could be used to measure the rate of formation of (spinning) supermassive black holes and/or clusters. To do this, however, requires not just an understanding of radio source physics (3), but also a renormalization to account for the missed quasar population. A quantitative understanding of how orientation affects the observed properties of extragalactic radio sources is therefore required to fully exploit these objects.
2 The receding torus

The ubiquity of the ‘big red bump’ longward of 1 \(\mu\)m in the spectra of QSOs (4), together with the interpretation of this as thermal emission from hot dust (5; 6), seems to indicate that dust will always exist as close to the active nucleus as physics allows. If this is the same dust that is responsible for hiding the nucleus from direct view in narrow-line objects, then it must lie further from the nucleus in objects with higher ionizing luminosities. The assumption that the height of the obscuring structure (‘torus’ in unification parlance) remains constant leads to the receding torus model (7; 8; 9). In this scenario, more luminous objects have a higher probability of being observed as quasars, and consequently the mean ionizing luminosity of quasars in an orientationally-unbiased (radio-selected) sample will be higher than that of radio galaxies. It therefore follows that any quantity which is more strongly correlated with ionizing luminosity than with radio luminosity will also be higher in quasars than radio galaxies (9). Indeed, studies of \([\text{O} \text{iii}]\) (10; 11), mid-to-far-infrared (12; 13), and submillimetre (14) luminosities indicate that quasars are indeed more luminous than radio galaxies in these properties by factors of a few. Since the receding torus model was first described at around the same time as the earliest of these studies, it has always surprised me that it did not gain greater acceptance as a way to explain these differences, which were incompatible with a picture where the torus opening angle was the same in all objects. The lack of a difference in \([\text{O} \text{ii}]\) luminosities between quasars and radio galaxies (15) is due to the insensitivity of this line to the strength of the ionizing continuum (9), while the apparent lack of a difference in \([\text{O} \text{iii}]\) luminosity at high redshift (16) is probably a result of large measurement uncertainties — the lack of a significant difference does not equate to the two classes having the same luminosity, and the data are also consistent with quasars being twice as luminous in this line, as is seen at lower redshift (11).

3 Observational evidence

Of course, the key assumption in the receding torus model is that the height of the torus is independent of AGN luminosity. While this seems to be a reasonable zeroth-order assumption, it need not be true since the AGN luminosity is correlated with black hole mass, and therefore also with the mass of the host galaxy; it is quite possible that either or both of these quantities might affect the height of the torus. However, several pieces of observational evidence indicate that the height of the torus is not a strong function of luminosity.

(1) The quasar fraction in different samples should increase with AGN luminosity as the inner wall of the torus is pushed away (17; 18).
Fig. 1. Relationship between optical and near-IR spectral indices (open and solid points, respectively) and rest-frame 1 μm luminosity for a complete sample of 3CRR quasars (20). The solid line indicates the relationship predicted by the receding torus model ($L_{2\mu m} \propto L_{1\mu m}^{0.5}$) for the near-IR spectral index only (with arbitrary vertical normalization).

(2) The fraction of lightly-reddened quasars (i.e., those where broad wings are seen on Hα but not Hβ) should decrease with luminosity as the solid angle over which lines of sight ‘graze’ the edge of the torus decreases (19).

(3) The strength of ‘big red bump’ relative to the ionizing continuum should be less in more luminous objects as the solid angle subtended by the torus decreases (20, 21). This is the cleanest and most quantitative test and the model fits the data well (Fig. 1).

Interestingly, there is also evidence that in the most luminous quasars, where the inner wall of the torus is pushed beyond a few parsecs, that the torus disintegrates completely (21). The most distant SDSS quasars therefore provide an accurate census of the number of supermassive black holes in the early Universe.

4 Implications

None of the pieces of evidence presented in the previous section is consistent with what some authors refer to as the ‘simplest’ unification scenario, where broad- and narrow-line objects are separated by a single critical angle, independent of AGN properties. This should not be a cause of concern, since
such a scenario is unrealistic, requiring either the inner walls of the torus to
unphysically remain at the same distance from the nucleus irrespective of the
AGN luminosity, or the torus height to increase in a contrived manner so as
to maintain a constant opening angle. In addition, the first and third points
above favour a torus rather than a warped disk since together they indicate
that the obscuration is caused by the hot dust close to the nucleus, rather
than by a warp at larger distances; the strong correlation between nuclear
extinction and viewing angle in narrow-line radio galaxies also favours a torus
rather than a warped disk (22).

As explained earlier, the receding torus model results in the mean (ionizing)
luminosity of quasars in a sample being brighter than the mean (ionizing)
luminosity of radio galaxies. The factor by which quasars are more luminous
depends on two quantities: (i) the mean opening angle of the torus in the
sample, which is fixed by the observed quasar fraction, and (ii) the spread
in the distribution of ionizing luminosities in the sample. This second quan-
tity is impossible to measure, but can be estimated as the convolution of
the observed radio luminosity distribution with a Gaussian representing the
scatter in the radio–ionizing luminosity correlation. Unfortunately, this scat-
ero is also unknown; I previously adopted 0.6 dex (9) from the scatter in the
radio–optical correlation (23), although the use of $M_B$ as a tracer of the total
ionizing luminosity adds uncertainties due to differences in rest-frame wave-
length, extinction, and optical/UV spectral index; tighter correlations do exist
(24) and I believe the true scatter is lower. For now, I shall leave this as a free
parameter.

The solid black region in Fig. 2 indicates that quasars exceed radio galaxies
by a factor of 2–20 for reasonable values of the $L_{\text{rad}} - L_{\text{ion}}$ dispersion (also, this
number is insensitive to the quasar fraction)\(^1\). These values are larger than
the factors of 2–5 by which quasars are observed to be more luminous than
radio galaxies (12; 11; 13; 14), but this is due to the simplistic assumption that
all tori have the same height. If torus heights are drawn from a log-normal
distribution, the overluminosity is reduced since it increases the likelihood of
low-$L_{\text{ion}}$ objects being seen as quasars (since some will have short tori) while
decreasing the likelihood of high-$L_{\text{ion}}$ objects being seen as quasars (since some
will have tall tori). This is represented by the gray regions in Fig. 2 where it can
be seen that a significant difference in luminosities persists even when the torus
height is allowed to vary by 1 dex. It is therefore inevitable that quasars will
be, on average, more luminous in their ionizing radiation than radio galaxies,
and hence more luminous in any related quantities (e.g., emission line and
infrared luminosities, which arise from the reprocessing of ionizing photons).
This is exactly what is observed, and adds additional support for the receding
torus.

\(^1\) Note that fig. 4 in ref. (9) is incorrect due to improper normalization.
Fig. 2. Factor by which quasars are more luminous than radio galaxies in an orientation-independent sample, as a function of the dispersion (assumed to be a Gaussian in log space) in the ionizing luminosities. The solid black region is for the simple receding torus model, where the spread represents samples with different quasar fractions from 30–80%. The other regions indicate what happens if there is a random spread in the heights of the tori in the sample, of factors of 2, 5, and 10 (1σ scatter), with 10 being the lightest gray colour.

5 Further studies

None of the observational results quoted in this paper arose from a deliberate attempt to test the receding torus model. However, the success of this model, together with the intriguing possibility that Fig. 2 could be used to estimate the scatter in the $L_{\text{rad}}$–$L_{\text{ion}}$ correlation and the range of torus heights, makes further study worthwhile.

First, the correlation in Fig. 1 should be extended to lower luminosities by studying fainter samples of radio-loud quasars at the same redshift (e.g., from the 7C sample); a sufficiently large number can be studied with an 8-m telescope in a few nights.

Second, direct evidence for an increase in the opening angle of the torus should be sought by looking at the distributions of the core-to-lobe ratio, $R$, in different samples. This measurement can be converted into an approximate viewing angle $\theta$ and the torus opening angle can be inferred from the distributions of quasars and radio galaxies.
6 Summary

The receding torus model provides a successful quantitative and physical framework within which to unify broad- and narrow-line AGN. The quantitative aspect is important for studies of the high-redshift Universe since neither optically-selected QSOs nor radio/optically-selected radio galaxies represent a fundamental class of object and their number densities must be related to the total (radio-loud) AGN number density by accounting for the missing population (narrow- and broad-line, respectively).

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