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An introduction to active galactic nuclei: Classification and unification

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ABSTRACT

In this article I present a summary of AGN classification, followed by a critical review of attempts to understand aspects of the classification in terms of orientation-based unified schemes. Concentrating on radio-loud AGN, I show that the unified schemes based on anisotropy induced both by beaming in relativistic jets and by absorption in dusty torus structures, work well in a broad-brush sense. However, they represent simplifications of a situation that is, in reality, likely to be more complex. In particular, the AGN selected in radio flux limited samples encompass a wide range of intrinsic X-ray/UV/optical/infrared properties for a given radio power, reflecting a number of variable factors in addition to orientation (e.g. large scale environment, accretion rate onto central black hole). There is also a growing recognition that AGN are dynamic, evolving objects that strongly influence their immediate surroundings, including the distribution of circum-nuclear gas and dust.

1. Classification

Classification is one answer to the question of how to make sense of a phenomenon with diverse properties such as active galactic nuclei (AGN). Classification is often one of the first steps taken in a scientific endeavour, and usually precedes – and indeed stimulates – understanding of the physical causes of the phenomenon in question. The history of science abounds with examples of classification as a first step in the road of understanding. Linnaeus produced a detailed classification schemes for living organisms long before they were understood as biological systems. Mendeleev developed the periodic table for the classification of the elements some forty years before it was explained in terms of atomic and nuclear structure.

The classic example of the success of the classification approach in astronomy is stellar spectral classification. After some earlier, less successful attempts by Secchi and colleagues, in the late 19th/early 20th century the Harvard group led by Pickering, Maury and Cannon succeeded in developing the stellar classification scheme that remains widely used today. Based on the relative strengths of detailed absorption features in the stellar spectra, and the requirement that the absorption line strengths vary smoothly and continuously along the sequence, the Harvard scheme identified some important patterns in the diversity of stellar spectra but was developed independently of any physical understanding of the stars. Such understanding only came with the subsequent development of atomic physics by Bohr and others, and the development of concepts such as ionization equilibrium and excitation of energy levels by, for example, Boltzmann and Saha. These developments allowed Payne–Gaposhkin to demonstrate that the Harvard spectral classification sequence is a sequence in photospheric temperature, and that the abundances of most common elements show little variation along the main sequence. This in turn aided the interpretation of the Hertzprung–Russell diagram, which underpins much of our understanding of stellar structure and evolution.

In many ways active galactic nuclei (AGN) represent a more diverse phenomenon than stars. Whereas stars emit most of their light in the optical atmospheric window, AGN emit powerfully over the full accessible electromagnetic spectrum. In consequence, AGN were discovered and classified separately at different wavelengths as technological advances allowed new parts of the electromagnetic spectrum to be opened up for astrophysical investigation. The main recognised classifications of AGN are summarised in Fig. 1.

The first recorded description of the optical spectrum of an AGN was made by Fath (1909) who noted the strong emission lines in the nuclear spectrum of NGC1068. However, the study of the nuclear regions of six unusual spiral galaxies by Seyfert (1943) represents the first systematic study of a class of AGN. The rich optical spectra of AGN generated considerable interest, and led to the eventual classification of Seyfert galaxies based on the presence (Seyfert 1 galaxies) or absence (Seyfert 2 galaxies) of broad (FWHM > 1000 km s^{-1}) permitted lines, in addition to narrow forbidden lines of [OIII], [OII], [OI], [NeIII], [NeV], [NII] etc. that are a feature of both classes (Khachikian and Weedman, 1974). The study of AGN gained considerable further impetus in the early 1960s following the discovery of quasars with their high luminosities, quasi-stellar appearance and optical spectra that are similar to those Seyfert 1 galaxies (Schmidt, 1963; Greenstein and Matthews, 1963).

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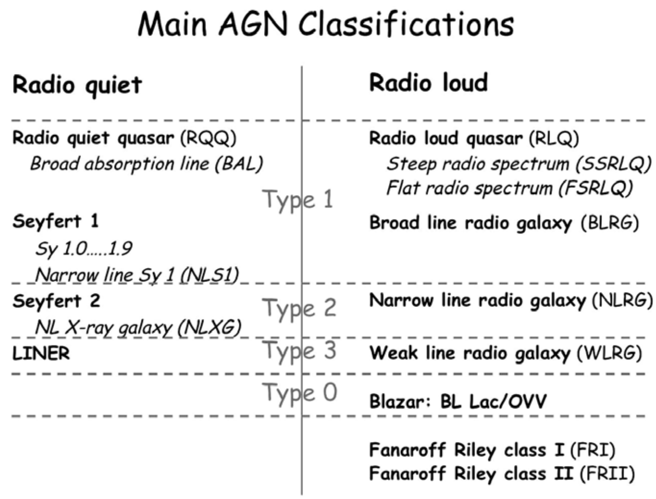

Fig. 1. The main classification labels used for active galactic nuclei. AGN with broad permitted lines detected at optical wavelengths are generally known as Type 1 AGN, while those with only narrow emission lines are known as Type 2 AGN. Lower luminosity AGN are sometimes referred to as Type 3 AGN, while those showing rapidly variability at optical wavelengths are sometimes labelled Type 0 AGN.

At the lower end of the luminosity scale it was clear by early 1980s that a large proportion of otherwise normal spiral galaxies show potential evidence for active nuclei in the form of low ionization nuclear emission line regions (LINERS:Heckman, 1980). However, it remains uncertain whether all LINERS are truly AGN, or rather a subset of them represent nuclear star forming regions (e.g. Ho et al., 1997).

Although AGN can be distinguished from stellar-photoionized HII regions based on their relatively broad emission lines and the unusual concentration of their emission towards the nuclear regions of the galaxies (c.f. Seyfert, 1943), such identification is not always clear-cut, and nowadays it is more common to identify AGN based on their emission line spectra, recognising the characteristic AGN spectra that encompass a wide range of ionization, as well as the presence of broad permitted lines some (Type 1) objects. This approach has recently been used with great success to identify many 1000's of AGN in deep wide field galaxy surveys based on fibre-fed spectrographs (e.g. Kauffmann et al., 2003).

The development of classification schemes for radio-loud AGN (i.e. those initially identified at radio wavelengths) has in many ways paralleled that of optically-discovered AGN. Following the first optical identifications of extragalactic radio sources by Bolton et al. (1949) and Baade and Minkowski (1954), it became clear that these "radio galaxies" often have rich emission line spectra that are similar to those of Seyfert galaxies (e.g. Schmidt, 1963), with broad line radio galaxies (BLRG) the radio-loud equivalent of Seyfert 1 galaxies, and narrow line radio galaxies (NLRG) the radio-loud equivalent of Seyfert 2 galaxies. There is also a class of weak line radio galaxies[1] (WLRG) which, despite the signs of powerful radio jet activity, have optical emission lines of low equivalent width and ionization (Hine and Longair, 1979; Laing et al., 1994; Tadhunter et al., 1998) – similar in many ways to LINERS. Finally, some radio-loud AGN are classified on the basis that they show rapid variability at optical wavelengths. Collectively labelled as "blazars", these include the BL Lac Objects (which also lack emission lines that strong relative to their optical continua) and optically violently variable (OVV) quasars.

To add a further layer of complexity, in addition to their optical classifications, it is also possible to classify radio-loud AGN on the basis of their extended radio structures. In the scheme developed by Fanaroff and Riley (1974), radio galaxies are classified according to whether they have extended radio structures are edge brightened or edge darkened (FRII or FRI). Significantly, FRI radio sources have radio powers that are, on average, lower than those of FRII sources, with the radio power dividing line between FRI and FRII sources falling close to the break in the radio luminosity function. The radio-loud quasars are also sub-divided on the basis of whether they are steep radio spectrum dominated (steep spectrum radio loud quasars: SSRLQ), flat radio spectrum dominated (FSRLQ), core-dominated or lobe dominated.

It is clear that the classification of AGN is complex and sometimes confusing, employing many different methods. Criteria include: the presence or absence of broad emission lines in optical spectra (e.g. Sy1/Sy2, BLRG/NLRG), optical morphology (e.g. Sy1/radio-loud quasar, BLRG/radio-loud quasar), radio morphology (FRI/FRII), variability (BL Lac, OVV), luminosity (e.g. Sy1/radio-quiet quasar, WLRG/NLRG), and spectral shape (e.g. SSRLQ, FSRLQ).[2] The general challenges faced in the classification of AGN include the following:

- *The diversity in classification methods.* The methods used to classify objects differ both between different wavelength regions, and within a given wavelength region, often leading to more than one classification applying to each individual AGN. Although this can be confusing, considerable insight may be gained by correlating the different classifications and properties of individual sources. For example, radio-loud quasars with flat radio spectra (FSRLQ) often have core-dominated radio structures and are highly variable at optical wavelengths (i.e. they are also classified as OVVs), whereas radio-loud quasars with steep radio spectra (SSRLQ) tend to have lobe-dominated radio morphologies and be less variable at optical wavelengths. Such patterns of behaviour lead to important insights in understanding the relationship between SSRLQ and FSRLQ (see below). As a further example, the fact that low power radio galaxies with FRI radio morphologies are invariably classified as WLRG at optical wavelengths provides key information about the physics of the energy generation in the central regions of such galaxies.
- *Attempting to force continuous sequences of properties into discrete bins.* A familiar problem from many fields of astrophysics is that, as part of classification, we often attempt to force objects that are actually continuous in a particular property into discrete classification bins. For example, it is now generally believed that radio-quiet quasars are high luminosity counterparts of Seyfert 1 galaxies, but there exists a continuous range in luminosity between the lowest luminosity Seyfert 1 and the highest luminosity quasar. Moreover the quasar classification is based primarily on optical morphology, whereas the Seyfert 1 classification is based mainly on optical spectroscopic properties. Therefore, it is hard to draw the dividing line in luminosity between the two classes. Similarly, because most AGN have non-thermal radio emission associated with the activity at some level, it can be difficult to draw the line between radio-loud and radio-quiet AGN. As a final example, the division between Seyfert 1 and Seyfert 2 galaxies is not always clear-cut, because the strength of the broad permitted lines relative to the narrow lines varies in a continuous manner. Hence the development of more detailed classification schemes in which Seyfert galaxies

[1] Following the definition of Tadhunter et al. (1998) WLRG are objects with $EW_{[OIII]} < 10$Å. Note that WLRG are sometimes labelled low excitation galaxies (LEGs).

[2] See Fig. 1 for an explanation of the acronyms.