Chapter 1

Quasars and Blazars

1.1 Quasars

This thesis is concerned with the optical emission properties of quasars. The advent of quasar research has been one of the most important advances in astronomy in the past half-century. These advances have helped to revolutionise the way we think of our universe, provided us with insights into many areas of exotic physics (from black holes to ultra-high energy gamma rays), and provided sources for every kind of astronomical detector. This chapter takes the form of a review of quasars and their (apparently) more extreme cousins the blazars. First, a note of clarification: the word "quasar" was traditionally used only for the radio-loud version, while radio-quiet quasars were known as QSOs (Quasi-Stellar Objects). It is becoming more common now to use quasar as a general term to refer to both types, and that practice is followed in this thesis.

1.1.1 The discovery of quasars

The discovery of quasars is an interesting tale in itself. The first radio surveys (such as the 3C or 3rd Cambridge survey) had poor angular resolution, so many sources were unable to be associated definitely with a particular optical source. In a classic piece of observational radio astronomy, a group of Australian astronomers (Hazard et al. 1963) used the lunar occultation of the radio source 3C 273[1] to pin down its location, by means of the diffraction pattern produced when the source disappeared behind the moon's limb.

[1]The 273rd object in the 3C or 3rd Cambridge catalogue of radio sources

The Caltech-based astronomer Maarten Schmidt was then able to locate the optical counterpart (using the 5m telescope at Mt. Palomar Observatory), and, in the position indicated by the radio observation, found two sources: a blue star and "a faint wisp, or jet" (Schmidt 1963).

This blue star, however, was obviously not an ordinary star. Its spectrum showed strong broad emission lines that Schmidt identified with the Hydrogen Balmer series, redshifted by $z = 0.16$. Schmidt concluded that this either made it a very compact star with a high gravitational redshift, or put it well outside the galaxy. This discovery prompted Greenstein and Matthews (1963) to look again at the spectrum of another radio source – 3C 48 – and they similarly found a redshift of $z = 0.3675$, based on lines of Mg II (until then only seen in UV spectra of the sun) and forbidden lines of Oxygen and Neon.

1.1.2 Quasars in the optical

After their detection at radio wavelengths, it was in the optical part of the spectrum that quasars were first recognised to be something peculiar. First of all, they had a very small size on the sky – the angular size of both 3C 273 and 3C 48 was $< 1''$. This similarity to the appearance of stars lead to the descriptive names of quasar (from quasi-stellar radio source) and QSO (quasi-stellar object). Besides this morphological description though, there were two other important observations.

Spectra

The first key feature that was noticed was the emission line spectrum that had initially so puzzled astronomers. The lines are very strong in emission (something not seen except in the hottest stars), featuring the elements of Hydrogen (the Balmer and Lyman series are prominent), Helium, Carbon and Magnesium, amongst others. The emission lines are also very broad. It was realised early on (Greenstein and Schmidt 1964) that this implied very large velocity widths for the line emitting gas – several thousand km s^{-1}. Together with the broad lines are narrow, forbidden lines (the strongest are [O III], [O II] and [N II]). These types of emission line features are seen also in the active nuclei of some local galaxies – the Seyfert galaxies. These are the low-luminosity analogues of quasars, where the host galaxy is visible. The different name comes from the different historical classification, although it is now widely accepted that type 1 Seyfert nuclei and quasars are the same type of object, in the sense that they are continually connected in luminosity. (The galaxies surrounding quasars are generally not seen due to their greater distance and the greater luminosity of the central object.)

The host galaxies of Seyferts are observed to be nearly always spirals, while quasars can occur in either spiral or elliptical galaxies. The exception are the radio-loud quasars and radio galaxies, which are predominantly in ellipticals. For example, approximately 89% of the low-redshift 3CR sources are in ellipticals (Martel et al. 1999).

The Seyfert galaxies come in two forms: type 1 and type 2 (also known as Sy1s and Sy2s). In both cases the galaxy has a bright, dominant nucleus. It is the optical spectrum of this nucleus that determines the difference between the two classes. The Sy1s show both broad and narrow emission lines, in a similar manner to quasars, while all the emission lines in Sy2s are narrow. The explanation for this difference will be discussed in Section 1.3. Collectively, quasars and Seyferts (as well as radio galaxies and low-luminosity galaxy nuclei called LINERs[2]) are known as AGN, or Active Galactic Nuclei.

Colour

The second key observation regarding the optical emission from quasars was the very blue nature of it. The first quasar identified, 3C 273, was found (Oke 1963; Schmidt 1963) to have a very blue optical continuum ($f_\nu \propto \nu^{0.28}$). This was found to be a general property of quasars and AGN, which distinguished them from stars: the hottest main sequence stars have $U - B \simeq 0.4 - 0.5$ mag, while typical AGN have $U - B \simeq -1$ mag (Krolik 1999). This proved to be a relatively efficient way to search for quasars – the so-called "UVX", or UV-excess method. A major example of this type of survey is the Palomar-Green (PG) Catalog (Green et al. 1986), which was the source catalogue for the Palomar Bright Quasar Sample (BQS) (Schmidt and Green 1983).

Another prominent optically-selected catalogue of quasars is the Large Bright Quasar Survey (LBQS, Hewett et al. (1995) and references therein).

[2]LINER = Low Ionisation Nuclear Emission line Region (Heckman 1980)

This is a catalogue of 1055 quasars, selected on the basis of their non-starlike appearance on objective prism photographic plates. The quasars had either strong emission (or absorption) lines, blue colour, or strong continuum breaks (i.e. utilising the two main optical features of quasars discussed above). This survey is therefore sensitive to all types of quasars except red quasars with featureless optical spectra (such as red BL Lacs – see next section).

Additionally, there is a major quasar redshift survey currently underway at the Anglo-Australian Observatory – the 2dF Quasar Redshift Survey (2QZ). This survey uses the 2 Degree Field multi-fibre spectrograph that is capable of taking spectra of 400 objects simultaneously. It thus is able to observe many more sources than previous surveys. The input catalogue contains over 46,000 objects, selected according to their $U-B/B-R$ colours (from APM scans of UK Schmidt plates), and the survey is expected to find some 25,000 quasars. As the survey is on-going, there is no final published catalogue, but see Boyle et al. (2000) for descriptions of the survey, as well as the first results on the optical luminosity function.

An interesting result of these large optical quasar surveys was the finding that only about 10% of all quasars are "radio-loud". The first quasars that were discovered were very bright in the radio (since that was the region of the spectrum in which they were found), but the vast majority of quasars that are now known are in fact radio-quiet. These quasars have a ratio of radio to optical flux of $\nu f_{\nu_r}/\nu f_{\nu_o} \sim 10^{-6} - 10^{-5}$, (note that although they are radio-quiet, they are not radio-silent!) while the radio-loud quasars have radio fluxes three to four orders of magnitude greater (Sanders et al. 1989). However, note that even in the radio-loud quasars, the radio emission comprises only about 0.1% of the total luminosity emitted over the entire electro-magnetic spectrum (Krolik 1999).

1.2 Blazars

There is a subset of the radio-loud quasars that have apparently extreme properties that set them apart from the rest of the population. These properties include rapid variability (at all frequencies and on all timescales), high polarisation (at both optical and radio frequencies), and, in some objects, a lack of any strong optical emission lines. The collective name that is usually applied to these objects is "blazar".

The name blazar originated, of all places, in an after-dinner speech by Ed Spiegel, at the Pittsburgh Meeting on BL Lac objects. The name is a combination of quasar and BL Lac, and has connotations of the characteristic optical variability and flaring that is seen in these objects. The use of the name in the literature is most likely due to the review of optical polarisation in extragalactic objects by Angel and Stockman (1980). However, the use today is still somewhat non-standardised. It has become quite common to describe the class of such objects as blazars, while it is probably more accurate to use "blazar" to describe the nature of the activity (i.e. "Source X exhibits blazar properties").

1.2.1 BL Lacertæ objects

Possibly the most famous sub-class of the blazars are the BL Lacertæ objects, or BL Lacs. These are named after their progenitor BL Lacertæ, which was originally classified as a blue variable star, and found to be the optical counterpart to the radio source VRO 42.22.01 (Schmitt 1968). Their defining feature is the lack of strong emission lines in their optical spectra. The commonly used definition (Stocke et al. 1991) is that the equivalent width satisfies $W_\lambda < 5$ Å. Additionally, if the Ca II H&K break (also termed the "4000Å break") due to the host galaxy is present, then the contrast[3] must be $\leq 25\%$. Marchã et al. (1996) modified this definition slightly to include sources with contrasts of up to 40%, with a relaxed restriction on the equivalent widths.

The cause of the lack of emission lines in BL Lacs has been the subject of much debate for the past twenty to thirty years. The most commonly used explanation (Blandford and Rees 1978, surely the most cited conference proceedings paper ever!) is that BL Lacs are viewed close to the axis of a relativistic jet. The (synchrotron) emission from this jet is Doppler boosted, increasing its intensity so that it swamps the continuum and line emission that would otherwise be visible.

The question of how exactly to define a BL Lac was complicated somewhat by the discovery by Vermeulen et al. (1995) and Corbett et al. (1996) of a broad Hα line in the progenitor of the class, BL Lacertæ. This observation

[3] The relative depression blueward across the Ca II break, so that a normal elliptical galaxy has a contrast of 50%.

was made at a time when the overall flux of the object was at a relatively low level (Maesano et al. 1997). These observations raise the prospect of there being a Seyfert-like accretion disk in the centre of BL Lacertæ, although present data is not quite suitable for discrimination between an accretion disk model or photo-ionisation by the synchrotron jet (Corbett et al. 2000).

For many years, BL Lacs were divided into two categories: radio-selected (RBLs) and X-ray selected (XBLs). The two categories had very different broad-band spectral energy distributions (SEDs): the RBLs peaked[4] in the IR to optical part of the spectrum, and were generally brighter at radio frequencies than XBLs; while the XBLs peaked at higher energies – into the X-ray part of the spectrum. The division into two categories was supported by a bi-modal distribution of the ratio of radio to X-ray flux. However, recent deeper surveys (such as the RGB, or *ROSAT* – Green Bank survey (Laurent-Muehleisen et al. 1999)) have filled in the gap between the two parts of the distribution, and the RBL/XBL terminology has made way for one that is less governed by the manner of selection. Instead, BL Lacs are more commonly referred to as LBLs or HBLs (low- or high-peaking BL Lac objects respectively) – referring to the location of the peak of the broad-band SED. Generally speaking (although by no means exclusively), sources that were known as RBLs are LBLs, and similarly for XBLs and HBLs. This categorisation has been used as part of attempts at BL Lac unification schemes (Fossati et al. 1998; Ghisellini et al. 1998).

1.2.2 Other blazars

As well as BL Lacs, the blazar class contains those quasars variously described as OVVs (Optically Violent Variables), HPQs (High Polarisation Quasars) or FSRQs (Flat-Spectrum Radio Quasars). These are quasars that share many of the same properties of BL Lacs (such as high polarisation and rapid variability), but with quasar-like emission lines. The different names come from the different classification schemes used: either by optical variability, optical polarisation or radio spectral index.

The name FSRQ is quite common, as it derives from the important fact that nearly all blazar sources have compact radio structure (i.e. are core-dominated) and tend to have flat radio spectra. A flat spectrum is typically

[4]This is a peak in a plot of νF_ν against ν, which gives the energy flux per logarithmic bandwidth.

defined as satisfying $\alpha > -0.5$, with $F_\nu \propto \nu^\alpha$.

1.2.3 Optical emission in blazars

The optical emission in blazars tends to be highly polarised, with levels of at least a few percent, and often much higher. This gives the first important clue as to the nature of this optical emission. A form of radiation that is naturally quite highly polarised is synchrotron radiation. This is radiation that is emitted when relativistic particles (such as electrons) move through a magnetic field. The particles spiral around the field lines, and as they do so they emit photons. The spectrum of synchrotron radiation covers a very broad range of frequencies – it can extend from radio frequencies (where it is found most often) up to optical and even X-ray energies. In blazars, the synchrotron emission is most likely to come from a relativistic jet that extends out from the centre of the source (although this is not always where synchrotron emission comes from – supernova remnants emit most of their radio emission in the form of synchrotron). A more complete discussion of synchrotron emission can be found in Chapter 3.

From examining the multi-wavelength SEDs of blazars (for example, Impey and Neugebauer 1988), it is found that a continuous, perhaps slightly curved, spectrum connects the radio, IR, and optical data points (and in some cases, the X-ray points as well). This, and the observed polarisation of the IR and optical, has led to models that invoke a single synchrotron component to explain the emission over this entire wavelength range. A further argument for synchrotron emission at optical wavelengths is the featureless continuum seen in BL Lacs. A continuum with no emission lines is precisely what you would expect when the emission is dominated by synchrotron.

What other components are there in the optical emission of blazars? For many objects, the synchrotron emission accounts very well for the continuum emission. In some, however, there is good evidence for emission from an accretion disk, which, as we shall see, is the dominant emission component in "normal" quasars. One example is the study by Malkan and Moore (1986) on two HPQs: PKS 1510−089[5] and PKS 0736+017. In both these cases, emission that is likely to be from an accretion disk was found to make up a quarter to a half of the visual light. There is also the case of the broad Hα

[5] This source, 1510−089, is part of the sample of quasars studied in this thesis

line in the spectrum of BL Lacertæ, which possibly indicates the presence of an ionising continuum from a Seyfert-like accretion disk (Corbett et al. 2000).

This brings us to the topic of emission lines in blazars. BL Lacs, by definition, have little to no emission lines present in their spectra, while HPQs have emission lines of the same strength as "normal" (that is, low polarisation) quasars. Scarpa and Falomo (1997) found that BL Lacs and HPQs had similar distributions of emission line luminosities, and suggested that the difference between the two classes was that BL Lacs had a stronger continuum. However, it is possible instead that BL Lacs have systematically weaker emission lines, due to a relative dearth of emission line gas. A further alternative (which may be the case with BL Lacertæ) may be that the accretion disk (if it is present) is weak, and so the ionising continuum is not sufficient to produce emission lines that are observable over the non-thermal (synchrotron) continuum. In other words, the lines are there, but they are just very weak. This is similar to the beaming hypothesis, but without requiring the stronger continuum. These issues will be discussed further in Chapter 7.

Finally, a word or two about the higher energy emission from blazars. The Energetic Gamma Ray Experiment Telescope (*EGRET*), on board the Compton Gamma Ray Observatory, detected gamma rays (at energies of >100 MeV) from at least 93 blazars (66 blazars were detected with high confidence, and the remaining 27 were low confidence detections) (Hartman et al. 1999). It was found that these "*EGRET* blazars" emitted more energy in the gamma ray region of their spectrum than any other. (See the figures in Appendix D for examples of these types of sources.) Also, a small number of blazars have been detected at even higher energies ($\gtrsim 1$ TeV), using Čerenkov detectors such as Whipple and HEGRA (see Petry (1999) for a review of the HEGRA detections).

The source of this gamma ray emission appears to be inverse Compton radiation, whereby highly relativistic particles interact with photons and "up-scatter" them, increasing the photon energy by a factor of $\sim \gamma^2$ (where γ is the Lorentz factor of the particle). If there is a significant amount of synchrotron emission, particularly at optical wavelengths, then the radiating particles are sufficiently relativistic to up-scatter any ambient photons to very high energies. The ambient photons can be the synchrotron photons emitted by the relativistic particles (in which case the up-scattered radiation is termed Synchrotron Self-Compton radiation, or SSC), or they can originate from some other source, such as the accretion disk, the broad line region, or even the cosmic microwave background (in which case it is termed External Compton radiation, or EC). This theory is able to explain quite well the broad-band spectra of blazars in terms of two broad peaks: the synchrotron peak, at low (i.e. IR to optical to soft X-ray) energies; and the Inverse Compton peak, at high (i.e. gamma ray) energies (see, for example, Fossati et al. (1998) or Ghisellini et al. (1998)).

1.3 The unified picture of quasars

From the observed properties of quasars and blazar AGN, we are able to construct a model for the structure of the central regions. Three key properties of quasars, that were recognised very early on (Greenstein and Schmidt 1964), give us a good insight into what is required to power quasars:

Luminosity: The large redshifts of quasars, if taken to be cosmological (a notion almost universally accepted now), imply very high luminosities. These luminosities can be as great as 10^4 times the total luminosity of a typical galaxy.

Size: Firstly, quasars are noted (indeed, often selected) to have a star-like appearance, i.e. unresolved to optical telescopes. This puts a limit of a few kpc to their size (depending on redshift and your choice of cosmology). However, the variability that is seen in many sources puts a far more stringent limit on the size. By converting the variability timescale into a physical size (from light travel time arguments), it is found that the emitting region (including the region from which the broad emission lines originate) must be ~ 1 parsec in size.

Emission lines: One of the defining features of quasars are the broad emission lines. These have velocity widths of thousands of km/s. As noted above, these emission lines originate within a few parsecs of the centre of the quasar.

The only model that has been successful at explaining how so much energy can be produced in such a small region has been accretion of matter onto a very compact, massive body – a black hole. The high velocities of the broad line region imply that they are orbiting a very massive object, and the only stable object so compact is a black hole.

The basic inferred structure of a quasar is then (starting at the centre and moving out):

‹ A massive black hole. The masses of these black holes range up to at least $10^9 M_\odot$. The massive elliptical galaxy M87 (not a quasar, but certainly the host of an AGN – see Chapter 2) has a black hole that has been measured at $(2.4 \pm 0.7) \times 10^9 M_\odot$ (Ford et al. 1994; Harms et al. 1994).

› An accretion disk. As matter falls in towards the black hole, it forms a disk which is heated by friction to quite high temperatures ($\gtrsim 10^5$K). This is believed to be the source of the strong continuum seen in (non-blazar) quasars.

An accretion disk is not the only method of creating the strong continuum. Barvainis (1993) proposed that free-free emission, from large numbers of small clouds of gas at high (10^5K–10^6K) temperatures. However, observations of broad Fe Kα emission lines in the X-ray from a few Seyferts (and possibly at least one quasar (Yaqoob and Serlemitsos 2000)) indicates that accretion disks may be necessary (the broadening fits that expected due to general relativistic effects originating in an accretion disk near a massive black hole).

fi Broad line region (BLR). A region extending from a few to hundreds of light days from the central black hole (known from reverberation mapping studies – see Netzer and Peterson (1997) for a review of the field). This is the location of the high-velocity gas ($\sim$ few thousand km/s) that is the source of the broad emission lines (Doppler broadened due to the high velocities) seen in the optical spectra.

fl Narrow line region (NLR). This region is much further out: $\sim$ 1kpc. This may be associated with the host galaxy, although it is illuminated by the central continuum source.

This basic structure is thought to be the same for Seyferts, although with an additional feature. The difference between Sy1s and Sy2s is explained very well by the presence of extra obscuration in Sy2s that blocks out the light from the BLR, leaving only narrow lines in the optical spectrum. This obscuration is thought to take the form of a "dusty torus" surrounding the BLR. Thus, Sy2s are viewed at an angle that intersects the torus, while Sy1s are viewed through the hole, enabling both the BLR and NLR to be seen. Whether such a torus exists for quasars is unclear. It has been postulated that a quasar analogue of Sy2s exists (the so-called type 2 quasar) (for instance, Halpern et al. 1999), and one or two may indeed have been detected by the X-ray telescopes *Chandra* (Fabian et al. 2000) and *BeppoSAX* (Franceschini et al. 2000).

Finally, the other key feature that is present, particularly in radio-loud objects (and, indeed, is very important for this thesis) is a jet. Radio galaxies (the other major extragalactic radio source aside from quasars) often show large radio lobes that extend up to megaparsecs away from the host galaxy. These lobes are connected to the host by a (usually thin) jet that, as seen in VLBI studies, reaches in to the innermost parsec of the galaxy. Such features are also seen in radio quasars, and are the source of the bulk of the radio emission. Also, some jets have been observed at higher frequencies, up to optical or even X-ray energies (see Chapter 2 for full details). The jets seem to emerge at right angles to the accretion disk, and thus impart a degree of axisymmetry to the structure of the nuclear region (a good example is the jet of the nearby AGN NGC 4258, which exhibits a sub-parsec radio jet elongated along the rotation axis of the disk (Herrnstein et al. 1997)).

This basic structure of a quasar (or, more generally, of an AGN) has formed the foundation for viewing angle unification schemes. The essence of these schemes is to explain the different observed properties of different types of AGN by the variation of the line-of-sight angle to the system (in other words, generalising the Sy1/Sy2 unification scheme).

This is particularly useful for radio-loud objects, due to the presence of the jet. The jet is relativistic[6], and so, if viewed close to its direction of

[6]This is known from observed superluminal motion seen with VLBI and *HST* in the inner parts of jets. Superluminal motion (i.e. motion at an apparent speed faster than c) requires reasonably relativistic speeds towards the observer at a small angle to the line of sight, and is a purely geometric effect caused by the features in the jet almost keeping up with the light that they emit.

propagation, the jet emission will be Doppler boosted (i.e. amplified) – this is known as Doppler beaming. Thus, the closer the observer is to the jet axis, the more dominant the jet emission will be relative to the emission from the accretion disk region. This is essentially the explanation for BL Lacs – that they are simply radio galaxies viewed close to the jet axis and the jet emission is far more dominant than the emission from the nucleus (which includes the emission lines).

This sort of unification scheme (Urry and Padovani 1995) unites BL Lacs with the low luminosity radio galaxies (Fanaroff-Riley type I, or FR I: Fanaroff and Riley (1974)), and FSRQs (or blazars with emission lines – generally more luminous than BL Lacs) with the more luminous FR IIs. These unification schemes are discussed further in Chapter 7.

1.4 This thesis

This thesis focuses on a sample of radio-loud quasars and AGN, with particular interest in their optical properties. The overall aim is to come up with consistent models that explain the optical/near-infrared emission, and examine the implications of these models for the study of radio-loud quasars in general.

Much of the modelling done is concerned with emission (more specifically, synchrotron emission) from the jet. Since we are looking at optical emission, Chapter 2 contains a review of those (few) sources that have observed optical jets (that is, optical counterparts to radio jets) and summarises the properties of those jets.

In Chapter 3, the theory behind synchrotron emission is examined, and is applied to a particular form of jet that may be expected to exist in the sources under consideration. The effects of relativistic boosting of the emission from the jet are also considered.

The remainder of the thesis contains the data and the results of the modelling. The sample of quasars used – the Parkes Half-Jansky Flat-spectrum Sample (Drinkwater et al. 1997) – is introduced, and the data (broad-band optical and near-infrared photometry) is presented for approximately one-third of the sample.

The models that are fitted to this data are presented in Chapter 5, as are the results of the model fitting. These results are then tested against the polarisation in Chapter 6 (since synchrotron emission is highly polarised, and many of the sources are HPQs). Chapter 7 contains an examination of the BL Lac objects in the sample, and how their properties are related to the rest of the sample's quasars. Chapter 8 contains an investigation of short-timescale variability of three objects from the sample at near-infrared wavelengths.

The key results of the thesis are summarised in Chapter 9, and the implications of the results in the context of other studies of radio-loud quasars and blazars are discussed.