Chapter 9

Conclusions and Discussion

9.1 Emission mechanisms

Synchrotron radiation is a very important emission process in quasars and AGN, due to its very broad band spectrum (extending over many decades of frequency) and its strong polarisation. It is the dominant process at radio frequencies in relativistic jets seen in radio galaxies and quasars, and in some jets (Chapter 2) this synchrotron emission is observed to extend to optical frequencies. Under unified models of AGN, such optical synchrotron jets are expected to exist in core-dominated quasars (such as those found in the PHFS), and this forms the basis for the modelling in this thesis.

A key observation that results from optical synchrotron jets is that the spectral index at optical frequencies is steeper than the average spectral index from the radio to the optical. This indicates that the synchrotron emission is turning over in the optical region – a feature that results from a cutoff or break in the energy distribution of the radiating electrons. This observation is supported by our modelling (see point ② below).

From the analytical theory of synchrotron emission, discussed in Chapter 3, we found that synchrotron emission from a highly ordered magnetic field will exhibit a strong dependence on the viewing angle. This dependence is of the form $L \propto (\sin\phi)^{2.5}$, where ϕ is the angle between the line of sight and the direction of the magnetic field. This finding is significant because it acts in the opposite sense to Doppler boosting. If plasma is moving with some relativistic bulk velocity in a direction close to the line of sight, then the observed flux will be strongly boosted. The amount of boosting will increase as the line of sight angle decreases.

Thus, the angular dependence of the synchrotron emission from an ordered field can decrease the effect of Doppler boosting, particularly at small angles to the line of sight. For such small angles, the bulk Lorentz factor Γ needs to be sufficiently large to be able to observe significant emission from the jet. Conversely, the fact that jets are visible at large angles to the line of sight (such as in radio galaxies), implies that the bulk velocities cannot be too great (else de-beaming occurs, resulting in a reduction of observed flux). The de-beaming is more pronounced for the ordered-field case, due to the relativistic aberration effect. This then places limits on how ordered the magnetic field in jets can be, in order for them to still be seen.

9.2 Data and modelling

It has to be emphasised that the modelling that was performed in Chapter 5 was made possible by the creation of the extraordinary data-set detailed in Francis et al. (2000) and Chapter 4. It is unprecedented in both the breadth and density of its coverage of the optical/NIR spectral region, and in the number of objects contained therein. Also, very importantly, all the observations are contemporaneous, which allows one to draw meaningful conclusions about the nature of the emission processes, confident that the effects of variability have been minimised (i.e. that, for each source, the ratio of fluxes in each pair of wave-bands is intrinsic to the source, and not because the source has varied during the interval between the observations).

The results of the modelling in this thesis can be summarised in the following points:

① Radio-loud quasars require at least two components to fit the rest-frame optical SEDs. These two components are well modelled by an optical power law, which in some sources is similar to the blue power law seen in optically-selected quasars, and a synchrotron component that turns over in the range $0.1\mu\mathrm{m} \lesssim \lambda_p \lesssim 3\mu\mathrm{m}$.

This is one of the very important results of the modelling in this thesis. Firstly, it shows that non-thermal radiation is important, or indeed dominant, at optical frequencies for a large fraction of the PHFS quasars. This synchrotron component is most likely connected with the radio synchrotron emission that comes from the relativistic jet, and so the jet emission extends over at least eight decades in frequency.

Secondly, the non-synchrotron sources are also important. In many studies performed on blazar AGN (including FSRQs), the dominant emission process that is used is synchrotron. It is very rare to see any other emission considered in the optical region, particularly when the broad-band SEDs (i.e. radio through X-ray) are considered (see Fossati et al. 1998, for example, as well as the discussion in Section 7.4.3). This work has shown that, for a large proportion of flat-spectrum radio quasars, synchrotron emission is in fact not dominant at all at optical wavelengths. It is undoubtedly present at some point in the spectrum, but the optical emission is dominated instead by emission that is most likely to be from the accretion disk region.

This draws out the fact that flat-spectrum radio quasars are quite heterogeneous at optical wavelengths – an observation caused, most likely, by the different cutoff wavelengths of the synchrotron component, and possibly by different strengths of the accretion disk as well.

② The model fits require the synchrotron component to have a break or turn-over at some wavelength λ_p in the observed wavelength range. A synchrotron spectrum with this break gives a much better fit to the data than a pure power law synchrotron model.

This break that is fitted to the data is a very sharp (exponential) cutoff. In this respect, the synchrotron emission is similar to that observed from optical jets in radio galaxies and quasars. These objects provide some of the only unambiguous detections of optical synchrotron emission (since the optical emission is coincident with the radio emission, is highly polarised, and is well fit by a synchrotron emission spectrum), and, as such, give strong support for the use of this type of spectrum.

The value of λ_p provides strong constraints on the modelling of particle acceleration and emission mechanisms. The sharp turnover is produced by an abrupt cutoff in the distribution of energies of the radiating particles. We have shown that such a cutoff is necessary to produce the required optical synchrotron spectra.

③ There is more than 4 orders of magnitude variation in the ratio of the synchrotron component to the power law component in those sources fit by the combined model. All the sources identified as BL Lacs lie at the high end of the distribution, although their distribution is not, statistically speaking, significantly different from that of the non-BL Lac objects.

This point again emphasises the heterogeneous nature of the PHFS at optical wavelengths. The sample includes blue quasars, dominated by power-law emission, through to red quasars and BL Lacs where the dominant emission component is synchrotron emission. Additionally, there is a continuum of variation between these two extremes, with many sources showing clear evidence of the presence of *both* components in the optical/NIR region. (A good example is 1510−089, which was found to have both accretion disk and "blazar" components in its optical spectrum by Malkan and Moore (1986), similar to the fit found in this thesis.)

④ The fits are statistically consistent with the data, and the fitting procedure is robust to reasonable changes in the values of the model parameters. Small changes in the assumed values of parameters such as the slope of the power law in the combined model do not change the overall complexion of the results (although the odd source may have a slightly different fit), and the conclusions drawn remain unchanged.

⑤ There may be an excess of red power law sources compared to optically-selected quasars. This will have implications for emission models of accretion disks.

These sources are quite puzzling. They do not appear to have any significant synchrotron emission in their optical spectra, nor do they show any evidence for dust reddening (due to their power law nature – a dust reddened source would be expected to show increasing curvature towards the blue). Yet they have redder slopes than typical blue quasars. Is this connected with their radio-loudness? Perhaps there is an interaction between the radio jet (or the outflow causing the jet) and the accretion disk region which produces this broader (and redder) range of colours. Closer spectroscopic analysis may be the best way to work out what is going on in these sources.

⑥ Sources which are well-fitted by power laws have a synchrotron component which may peak in the IR. In the optical, these sources are similar to optically-selected quasars.

All the PHFS sources have synchrotron emission dominating at radio frequencies. Yet the optical/NIR SEDs for the bluer sources show no evidence for synchrotron emission – they are well described simply by the blue power law seen in optically-selected quasars. Presumably the synchrotron emission must cut-off somewhere between the radio and the optical. These infrared (or even submillimetre) cutoffs would constitute the extension of the distribution of λ_p seen in Fig. 5.6.

On the other hand, the distribution of λ_p may not continue very far to shorter wavelengths than those investigated here. There are a few pieces of evidence to support this. Firstly, the redshift distributions of the sources with combined fits and power law fits (Fig. 5.10) indicated that there may be a lack of short-wavelength-peaking synchrotron components, thereby producing the observed redshift differences. Secondly, there are no observed synchrotron jets with synchrotron spectra that extend into the X-ray region. All observed optical jets show spectra that are steeper in the optical than the radio–optical slope, indicating that all these spectra are turning over in the optical region. Finally, the lack of power law synchrotron fits indicates that there are few, if any, sources with turn-overs at shorter wavelengths than those considered here. Thus, the distribution of λ_p values that we find from the modelling represents the short-wavelength end of the overall distribution.

⑦ Optical polarisation measurements (taken from the literature) support the synchrotron model fits to the SEDs. Firstly, there is a correlation between the polarisation and the colour, with the red sources being more highly polarised. Secondly, the highly polarised sources are fit with large amounts of synchrotron.

Near-infrared polarisation measurements lend some support to the fitted models, but, in general, the polarisation measurements do not cover a great enough range in wavelength to effectively discriminate between different models. The way to remedy this would be to obtain simultaneous optical and near-infrared polarisation measurements.

⑧ Both the power law emission (which is likely to be from the accretion disk) and the synchrotron emission can be variable. We observed micro-variability on timescales of hours in a source that showed no evidence for the presence of synchrotron (to which variability is usually attributed), indicating that the accretion disk emission can experience rapid flux variability.

⑨ Finally, the red component fitted to the data, which we have modelled as synchrotron emission with a turnover at some peak wavelength, cannot be hot dust. Emission from hot dust cannot peak at $\lambda_{\rm rest} < 1.66\mu$m as is required by the data. This establishes that the NIR emission in the PHFS is, at least in part, of a different origin to that seen in radio-quiet quasars (Sanders et al. 1989).

9.3 The nature of radio-loud AGN

9.3.1 BL Lacs

Due to the diverse nature of the AGN found in it, the PHFS provides us with a basis to study the relationship between the different classes of radio-loud AGN. We examined this in Chapter 7, by exploring the relationship of the BL Lac objects to the rest of the PHFS. We found that, optically, the only differences between the two classes were that BL Lacs were redder (particularly in comparison to the power law objects), and that the BL Lacs had smaller emission line equivalent widths. The distributions of all other fitted properties were consistent with being the same for all objects. We found that the most likely explanation for the small equivalent widths was a relative lack of gas in the BL Lacs to provide the emission line flux.

Under this picture, then, the BL Lacs are simply versions of synchrotron-dominated quasars that are relatively deficient in emission line gas. The emission that is observed from the BL Lacs is strongly dominated by the synchrotron emission (see Fig. 5.7), as is the emission in a number of quasars that show relatively large emission lines – only very weak, if any, power law emission is seen in these objects.

We note here that the synchrotron emission in the BL Lacs is observed in the optical only because it has not turned over at a longer wavelength. In other words, λ_p cannot be too great, else the synchrotron emission will not be seen. It is reasonable to expect, however, that this will not always be the case. It is likely that there are some BL Lacs (i.e. sources with very weak emission line fluxes) that have their synchrotron spectrum turning over at sufficiently long wavelengths that there is little contribution in the optical. At large enough redshifts, the host galaxy will not be seen, and so these sources will appear to be either very faint sources or empty fields.

Conversely, at low redshifts, the light from these BL Lacs will be dominated by the host galaxy. We therefore would expect that there are some BL Lacs buried at low luminosity inside a comparatively bright galaxy. According to definitions of BL Lacs (Marchã et al. 1996; Stocke et al. 1991), as well as having weak emission lines, the spectrum should not exhibit too strong a contrast across the 4000Å break. This assumes, however, that the BL Lac (as opposed to its host galaxy) has significant optical emission. These definitions, therefore, introduce a bias against BL Lacs that have their non-thermal component turning over before the optical region, yet still have low optical emission line fluxes.

How might these "optically-quiet" BL Lacs appear? Optically, they would seem to be a relatively normal galaxy (presumably elliptical, as are the host galaxies of most radio-loud AGN), whereas, at radio frequencies, they would have a flat spectrum core, and possibly similar extended emission to "normal" BL Lacs. Objects such as these may have been found in the 200 mJy flat-spectrum sample of Marchã et al. (1996) – they are discussed by Antón and Browne (1999), who interpret them in terms of an orientation model. It should be possible to search for such objects – for example, correlating galaxy and radio surveys to find otherwise unremarkable elliptical galaxies (or PEGs: passive elliptical galaxies, to use the acronym from Antón and Browne (1999)) that exhibit a flat-spectrum radio core.

9.3.2 Unification models

What can we say from the modelling presented in this thesis about possible unification models for radio-loud AGN? The discussion in Section 7.4.3 showed that these questions are largely unresolved, although this work can help shed some light on this area.

Firstly, the low emission line fluxes that we observe in the BL Lacs are consistent with them having FR I radio galaxies as their parent population (although we note that low-excitation FR IIs have also been suggested as possible parents of BL Lacs (Laing et al. 1994), and this is certainly not ruled out or in by our work). The other interesting point as far as these models are concerned is the observation that, apart from the emission line properties, there is little to distinguish the BL Lacs from the other synchrotron-dominated quasars. Does this have any implications for the idea of FR IIs being the parent population of FSRQs? The fact that the distribution of synchrotron peaks and strengths are very similar in both the BL Lacs and quasars probably indicates that the regions in the jets from where the optical synchrotron emission originates have similar properties. This may indicate that the jets themselves in FR Is and FR IIs have similar forms (e.g. velocity structures). We do note that many FR I sources show VLBI-scale jets that are similar to those seen in FR IIs (Giovannini et al. 1995; Parma et al. 1987), possibly indicating that the jets in both types of radio galaxies start off with relativistic velocities, but are then slowed down in FR Is (perhaps due to interactions with the ambient medium) (Laing et al. 1999).

Secondly, the comparison with the "two-peak" unification scheme (Fossati et al. 1998) raised a couple of points of interest. The scheme was developed using quite bright samples in both the X-ray and the radio, and by comparing these with the PHFS sources we have shown that the scheme is not as successful for the lower luminosity quasars. Also, this particular scheme did not account for the presence of the power law emission that is dominant in many of the PHFS sources. This was obvious in the colour-colour plot (Fig 7.7d), where most of the PHFS sources had radio–optical slopes below that predicted by the pure synchrotron model. This is consistent with there being an additional (non-synchrotron) component at optical wavelengths.

This last point demonstrates the importance of taking into account emission from the accretion disk in modelling radio-loud quasars. Our modelling presented in this thesis has shown that both the synchrotron emission *and* the accretion disk emission are important in explaining the optical emission of all types of radio-loud flat-spectrum objects. As we have seen, in most attempts at modelling the optical emission of radio-loud AGN, generally only one of these components is considered to be dominant. However, we have shown that, in a sample that is selected to be quite homogeneous at radio frequencies, both of these optical emission mechanisms are important.

9.4 Future directions

This section details how the work presented in this thesis could be extended, either by further observational campaigns, or via theoretical studies.

Polarisation: Polarimetry of quasars and BL Lacs in the optical and near-infrared provides an excellent way of determining the main emission components, due to the high intrinsic polarisation of synchrotron emission. The NIR polarisation data presented and discussed in this thesis, while somewhat supportive of the presence of synchrotron, did not have the necessary wavelength coverage to effectively discriminate between different models (such as the combined model or a pure synchrotron model).

It would be ideal to obtain contemporaneous optical *and* NIR polarisation measurements of a range of objects, in order to get an accurate idea of the wavelength dependence of the polarisation over a substantial range of wavelengths.

Micro-variability: The key finding of the micro-variability study is related to the last point of the previous section. Of the three sources examined, the one that we can confidently say exhibited significant micro-variability was the source that showed no evidence for synchrotron emission in its optical–NIR SED. This shows that the accretion disk emission can exhibit short-timescale variations, a property widely ascribed to synchrotron emission from a jet. Thus, both mechanisms will be important in describing blazar emission.

The relative importance of the micro-variability of the accretion disk and synchrotron emission will need to be gauged from a more thorough investigation of micro-variability properties of radio-loud AGN. A suitable sample to use would consist of sources both with and without optical synchrotron emission (also including BL Lac objects). By observing a larger sample of objects, the results will be able to be put on a more quantitative footing. This followup can be done either in the optical or near-infrared, although optical imaging is preferable due to the larger field of view (compare CCD imaging with the 1m with CASPIR on the 2.3m). This enables greater numbers of comparison stars to be observed, thereby providing greater accuracy in the light curve.

Multi-filter observations: The modelling presented in this thesis was made possible by the compilation of the large data set of optical and near-infrared photometry. This was a considerable undertaking[1], not least because each data point required a separate observation. In future, however, this problem may be (partially) circumvented by the advent of multi-filter cameras, such as those used in the surveys SDSS[2] and 2MASS[3]. These cameras can take images of the sky in a number of different filters at once, thereby providing totally simultaneous observations in all these bands (which, as we have seen, is crucial for studies of quasars and BL Lacs). The SDSS will provide images of one quarter of the sky in five broadband optical filters, and will thus provide a great resource for studying the optical emission of the hundreds of thousands of quasars that are expected to be found (100,000 of which will be followed up spectroscopically to determine redshift).

Jets: The examination of the different synchrotron emission models in Chapter 3 showed that emission from ordered magnetic fields has different properties to that from tangled fields – a key property being the strong angular dependence of the emission, which has implications for Doppler beaming of jets. These jet models, however, are quite simple, with the jet essentially being a uniform, straight tube. The next step in this modelling would be to construct models that are better representations of real jets, including properties such as a changing radial magnetic field strength.

Also, the relative importance of the ordered and tangled field models needs to be explored in the context of real jets. Polarimetry observations of the M87 jet (Perlman et al. 1999) have shown that the knots in the jet tend to be highly polarised, and so are likely to have highly ordered magnetic fields. There are other regions, however, that have relatively high emission but little polarisation – these regions are likely to have tangled fields. The relative strength of these types of regions, particularly as a function of jet power (in the sense of the FR I / FR II division) will have important consequences for orientation-dependent unification models.

Finally, we note that while the synchrotron models that were fitted to the data provided very good fits, the lower-frequency part of the spectrum was not constrained. It would be good, in future, to examine the connection between the optical synchrotron emission and the radio synchrotron emis-

[1]One for which Paul Francis deserves a great deal of praise!
[2]The Sloan Digital Sky Survey: http://www.sdss.org
[3]The Two Micron All Sky Survey: http://www.ipac.caltech.edu/2mass/

sion. A look at the broadband SEDs (Appendix D) shows that it is difficult in many cases to imagine a single synchrotron component (certainly of the simple forms discussed in Chapter 3) fitting both the radio and optical data points. (Remembering of course that these points are not simultaneous!) There are a number of key questions that remain unsolved in this area:

- Do the optical and radio emission come from a single component?
- If not, how is the optical emission connected with radio?
- Are there extra components in the radio that do not extend up to the higher frequencies? Where in the quasar/jet are these components from? How far in frequency do they go?
- Finally, what makes a flat radio spectrum (such as we see in the PHFS sources) flat?