Chapter 2

Optical jets and their properties

An important feature in the unified model of AGN, particularly radio-loud AGN, is the jet. This is a relativistic outflow from the central regions of the AGN, and is a major source of radio frequency emission (through the synchrotron process) in radio-loud objects. The other major sources are the large lobes often seen in radio galaxies, although these are stronger at low radio frequencies than high.

Since the work in this thesis is concerned primarily with the optical and near-infrared emission of radio-loud quasars, the amount of optical emission that comes from the jet is of considerable interest. This chapter contains a review of observations of optical counterparts to radio jets, and a summary of the relevant properties, particularly the spectral indices of the jet and the angle the jet makes with the line of sight.

2.1 Observed optical jets

Only a small number of optical counterparts to radio jets in active galaxies have been observed, despite the large number of radio jets that are known. The main reason for this is that, with a couple of notable exceptions, they are faint and small (in breadth, if not length). The rapid increase in the number of optical jets known in the past decade has been primarily due to the advent of the *Hubble Space Telescope (HST)*, with its unsurpassed resolution, although some have been discovered via ground based telescopes,

Name	Other names	Redshift of host	Host type
3C 15	PKS 0034−014	0.073	E1
3C 66B	0220+424	0.0215	E
3C 78	0305+039 NGC 1218	0.0289	S0/Sa
3C 120	PKS 0430+052 II Zw 14	0.033	S0
PKS 0521−365		0.055	E
3C 200	0824+294	0.458	?
3C 212	0855+143	1.049	?
3C 245	1040+123	1.029	?
3C 264	1142+198 NGC 3862	0.0216	E
3C 273	1226+023	0.16	E4
M87	1228+126 3C 274 Virgo A NGC 4486	0.004	E1
3C 346	1641+173	0.161	E
3C 371	1807+698	0.051	E
3C 380	1828+487	0.692	E
PKS 2201+044		0.028	E

Table 2.1: Sources that exhibit optical jets that are coincident with radio synchrotron jets. Other names lists common names by which the sources are known (positions are B1950). The redshift and morphological type (where known) of the host galaxy is also shown (generally taken from NED, the NASA/IPAC Extragalactic Database).

notably several using the *Nordic Optical Telescope (NOT)* on La Palma. Those sources with optical jets are listed in Table 2.1, and descriptions of the individual sources follow.

M87: The famous jet in M87 is the oldest known and most studied of all optical jets, primarily because of its high surface brightness and proximity to Earth. In 1918, the astronomer Heber Doust Curtis observed it during a study of M87, describing it as a "curious, straight ray" (Curtis 1918). M87 was later discovered to be a strong radio source (Virgo A), and the non-thermal nature of the jet was confirmed by Baade (1956), by detecting its strong optical polarisation. It was already known to have a blue featureless continuum and to be associated with radio emission – in the same manner as the Crab Nebula.

M87 itself is a giant elliptical (in fact, one of the most massive known – it has a mass of up to $\sim 10^{14} M_{\odot}$ (Mathews 1978)) at the heart of the Virgo cluster. It was first discovered by Charles Messier, in his famous catalogue of Nebulae and Star Clusters (Messier 1781), and has been the subject of much study throughout this century.

Narrow-band imaging and spectroscopy by the *HST* have revealed the presence of a disk of ionised gas, surrounding a black hole of mass $2.4 \pm 0.7 \times 10^{9} M_{\odot}$ (Ford et al. 1994; Harms et al. 1994). This mass is actually obtained from the velocities of the disk and is the mass internal to a radius of $0''.24$ (or 18–20 pc), which, with a mass to light ratio of $M/L \sim 170$, implies the presence of a black hole.

The jet itself shows remarkably similar structure at both optical and radio frequencies, which is seen in both continuum images and polarisation images. The brighter knots in particular show evidence for a steepening of the spectrum in the optical (Meisenheimer et al. 1996), indicating that the spectrum turns over at optical frequencies.

3C 273: The jet in 3C 273 is the second oldest known optical jet. It was first noted by Schmidt (1963) (describing it as "a faint wisp or jet") in the paper that first reported 3C 273's large redshift.

The structure of the 3C 273 jet is atypical for optical jets. The radio emission is much more extended, both laterally and longitudinally, than the optical emission, with the optical jet running along the ridge line of the radio emission (Morrison and Sadun 1992; Thomson et al. 1993). The radio features generally coincide with the optical knots, although the bright radio head of the jet is not seen in the optical (Bahcall et al. 1995). It is possible that the optical jet emission is not pure synchrotron (Thomson et al. 1993), but may include either some scattered quasar light or starlight.

The host galaxy has been shown (Bahcall et al. 1997) to be a bright E4 elliptical. Indeed, at $M_V = -22.1$, it is brighter than the brightest galaxy of a rich cluster. It seems to be in a group of several galaxies.

3C 15: This source is an elliptical galaxy, classified as an intermediate FR I / FR II. The optical counterpart to the jet was discovered by Martel et al. (1998), using *HST*. The optical jet matches the inner part of the radio jet, although the two radio knots are undetected in the optical.

Interestingly enough, the nucleus of 3C 15 appears to lack a sharp pointlike AGN, possibly indicating that the source is in an inactive state. What is seen, however, are three ridges of emission extending out from the nucleus, along with a dark dust band, which seem to point to a merger event.

3C 66B: This optical jet was detected by Butcher et al. (1980) using a vidicon video camera on the 4m Mayall telescope at Kitt Peak. At *HST* resolution (Macchetto et al. 1991a), the jet shows filamentary structure, with evidence for two strands. This has not been seen in any other optical jet except M87, which shows a more tightly bounded structure, possibly indicating a different interaction with the medium. Fraix-Burnet (1997) found evidence for an optical counter-jet (3C 66B is the only optical jet source that shows a radio counter-jet), which, if confirmed, would cast some doubt on the beaming model for jets.

3C 78: The optical jet in 3C 78 was discovered by Sparks et al. (1995). The jet shows a "remarkable" coincidence between the radio and optical morphologies and direction (that is, the position angles are the same). The host galaxy is notable for being a spiral (an S0 at least), as well as showing Seyfert 1 characteristics.

3C 120: 3C 120 is classed as a Seyfert 1 galaxy, and so is rare in not being an elliptical host. It has a variable AGN, is a powerful X-ray source (Maraschi et al. 1991), and has a radio jet with superluminal motion (Walker et al. 1988). A faint optical counterpart to the jet was detected using the *NOT* (Hjorth et al. 1995). One of the "condensations" was found to be polarised ($p = 12\% \pm 4\%$), thus linking it with the radio jet. The overall structure of the optical jet coincided with the radio, although no counterparts to the radio knots could be discerned. It is possible that the optical emission is not pure synchrotron (similar to 3C 273) – there could be some scattered starlight present as well.

PKS 0521−365: This is an elliptical radio galaxy that exhibits a bright radio nucleus, along with extended radio emission. In *HST* observations (Macchetto et al. 1991b), a bright knot was seen at the same place as in *VLA* data. After this, the jet has roughly constant surface brightness.

However, in *HST* snapshot survey observations (Scarpa et al. 1999), this bright knot is not seen. In these observations, the jet has an almost constant width along its length, which implies that the plasma is moving in a well-defined cylindrical funnel. There is also a general one-to-one correspondence between the radio and optical morphologies.

3C 200: In their *HST* snapshot survey of 3CR sources, de Koff et al. (1996) detected a narrow feature extending southeast from the core of this quasar. The direction and morphology of the radio jet is "practically identical", and so they suggest this is a very strong candidate for an optical jet. However, a longer exposure image than that taken in the snapshot survey would be required to obtain better analysis of this jet.

3C 212: This is one of the highest redshift sources known to exhibit optical counterparts to radio jet structures. With an absolute magnitude of $M_V < -24$, it is more accurately described as a quasar, rather than a radio galaxy. It was imaged with *HST* and Keck by Ridgway and Stockton (1997). It shows a peculiar morphological structure, with a number of blue optical components lying along the radio jet axis. It also shows an extended structure that Ridgway and Stockton speculated could be the optical counterpart to the radio lobe, but was shown (Stockton and Ridgway 1998) to more likely be a neighbouring galaxy.

3C 245: This, too, is a bright, high redshift quasar ($M_V < -26$), also imaged by Ridgway and Stockton (1997). These images show a linear feature that coincides exactly with the radio jet, and since there is good correspondence between the optical and radio structure, it is likely the optical emission is due to synchrotron radiation.

3C 264: This optical jet was discovered by Crane et al. (1993). The radio and optical jets show a very good spatial coincidence. There is also a 'ring' of enhanced optical emission at a radius of 300-400 pc from the nucleus, which Baum et al. (1997) interpret as most likely due to the presence of a face-on dusty disk. The jet widens dramatically after passing through this disk and becomes turbulent, changes direction, and fades rapidly. This is most likely due to decreased pressure in the ambient medium outside the disk/ring.

Lara et al. (1999) have shown that the optical emission is most likely due to synchrotron emission (and not Inverse Compton or scattering), but that likely explanations of re-acceleration have some problems. In particular, well defined knots are required along the jet, and these are not seen. Also, it is unclear how the radio-optical spectral index is kept approximately constant along the jet.

3C 346: Optical emission associated with a radio knot was discovered (Dey and van Breugel 1994) in this FR II radio galaxy, using ground based imaging in the optical/ultraviolet. *HST* snapshot imaging by de Koff et al. (1996) resolves this knot into a curved jet and a triple hot spot that coincides perfectly with the radio emission.

3C 371: 3C 371 is classed as a BL Lac object and exhibits a one-sided radio jet. The optical jet was discovered using the *NOT* by Nilsson et al. (1997). The radio and optical morphologies do not exactly coincide, with the radio jet being several times longer than the optical (Scarpa et al. 1999), in a manner somewhat reminiscent of the jet of 3C 273, and unlike other jets such as those of M87 and PKS 0521−365.

3C 380: This object is a radio-loud quasar, classified as a compact steep-spectrum source by Fanti et al. (1990). The radio jet shows two prominent knots that are seen in the optical (O'Dea et al. 1999). There is a good one-to-one correspondence between the optical and radio emission in both the knots. Due to the large redshift of the source, these knots are the most luminous known.

PKS 2201+044: The optical jet in this source was discovered (Scarpa et al. 1999) during the *HST* snapshot survey of BL Lac objects, and so the exposure time was less than ideal. However, the jet was able to be resolved, and the association with the radio jet was established. A final point to note is that, although 2201+044 is classified as a BL Lac, it shows broad emission lines in its spectrum, and so the beaming cannot be very strong (perhaps due to a large angle to the line of sight).

There are a number of other sources that are possible candidates for optical jets. De Koff et al. (1996) found a further 8 candidates for optical synchrotron jet emission, including 3C 20 (the optical counterpart of a hot spot was detected by Hiltner et al. (1994)), 3C 133 and 3C 410. As these observations were made with *HST* in snapshot mode (which involves shorter exposures than are ideal), longer exposure imaging may be expected to resolve these jets. In addition to these sources, a number of sources have been shown to exhibit optical emission associated with a radio hot spot (Dey and van Breugel 1994; Meisenheimer et al. 1989).

2.2 Observed properties of optical jets

In this section we list and discuss some of the observed properties of the optical jets, in particular their length and viewing angle, and the spectral indices (both optical and ratio-optical). All of these parameters are important in constraining the models that will be used for the synchrotron emission from the Parkes quasars, as well as beaming models for quasars and BL Lacs (Chapter 7).

2.2.1 Power law indices

A relatively easy parameter of optical jets to measure is the spectral index, which is defined (for this discussion) as α, where $F_\nu \propto \nu^{-\alpha}$. This is usually determined on the basis of two points: a radio and an optical observation, giving the radio–optical slope α_{ro}, or two different optical wavelengths for the optical slope α_o. The spectral index gives one an idea of the average slope of the continuum over the frequency range under consideration, which allows the emission mechanisms to be constrained.

Since all the optical jets have radio counterparts, α_{ro} gives information on how the optical emission is connected to the radio emission, and this can help determine whether the optical emission is synchrotron as well (since the radio emission is widely accepted to be due to the synchrotron process). The optical slope can also give information on the emission processes at the higher optical frequencies, without worrying about the radio emission.

Table 2.2 lists the measured spectral indices for all optical jets as taken from the literature. At first glance, several things are immediately apparent. The average values for the spectral indices are $\langle\alpha_o\rangle = 1.41\pm0.33$ and $\langle\alpha_{ro}\rangle = 0.79\pm0.13$. Even though there is some scatter in the values, it is clear that the α_o values are steeper than the α_{ro} values.

This is consistent with a synchrotron component that cuts off or turns over at some maximum frequency. This in fact has been postulated as one reason for the low number of sources seen with optical jets (as compared to the number of sources with radio jets), as most of the sources without optical jets have this cut off at a frequency lower than optical frequencies.

We note that, from Table 2.2, the values of α_o, while there are a couple above 2.0, are mostly clustered around values of $1.3-1.4$. Is this significant? If the optical slopes were much steeper, the jet emission would be harder to detect, since they will in general be fainter, and so jets with steeper optical indices will tend to be selected against. On the other hand, a flatter optical slope would not be selected against, and so the absence of flat optical slopes (i.e. slopes that are closer to or the same as the radio–optical slope) appears

Name	α_o	α_{ro}	ref
3C 15	1.2	—	8
	—	0.95	7
	—	0.86	10
3C 66B	1.6	0.80	1
	2.4	—	8
3C 78	1.2	—	8
	—	~ 0.69	3
	—	0.81	10
3C 120	1.3	0.65–0.69	2
	—	0.69	10
3C 200	—	0.74	10
PKS 0521−365	2.0	0.76	1
	1.4	—	8
	—	0.73	7
3C 212	1.4	—	8
	—	1.06	10
3C 245	1.2	—	8
	—	1.03	10
3C 264	1.4	0.58	1
	1.34	0.63	6
	1.4	—	8
	—	0.85	10
3C 273	1.33	0.90	1
	1.3	—	8
	—	1.07	10
M87	1.2	0.66	1
	0.97	0.65	4
	1.2	—	8
	—	0.71	10
3C 346	1.8	—	8
	—	0.87	10
3C 371	—	0.81	5
	—	0.75	9
	—	0.74	10
3C 380	1.2	—	8
PKS 2201+044	—	0.85	9

Table 2.2: Table showing spectral indices α (where $S_\nu \propto \nu^{-\alpha}$). The indices given are the optical (α_o) and the radio–optical (α_{ro}). References: (1) Crane et al. (1993); (2) Hjorth et al. (1995); (3) Sparks et al. (1995); (4) Meisenheimer et al. (1996); (5) Nilsson et al. (1997); (6) Lara et al. (1999); (7) Martel et al. (1998); (8) O'Dea et al. (1999); (9) Scarpa et al. (1999); (10) Scarpa and Urry (2001)

to be a real one. That is, there are not significant numbers of jets with synchrotron spectra extending to UV and X-ray energies.

2.2.2 Jet length and viewing angles

The length of observed optical jets can be a difficult parameter to measure. Quite obviously, it depends on the capabilities of the telescope being used, as the end of the jet needs to be able to be resolved and detected significantly above the background. Even when the end of the jet is able to be defined, the apparent length of the jet is still only the projected length – that is, the jet is seen projected onto the plane of the sky. For this reason, jet length and the viewing angle, or the angle that the jet makes to the line of sight, are tied together.

The length of the jet can provide information on both the power of the central source (depending on models of how jets are formed and therefore how they connect to the central black hole), as well as the nature of the interstellar and intergalactic medium. A list has been compiled of jet lengths (in both arcseconds and kiloparsecs) in Table 2.3. The lengths span nearly two orders of magnitude, with the powerful quasar 3C 273 having the longest. However, these lengths are of course projected lengths, so viewing angle effects have not been accounted for.

Since the jets are seen in projection against the plane of the sky, this viewing angle is quite a difficult parameter to measure. As well as being important for determining the correct lengths of jets, this angle is also important for determining the Doppler factor, and hence the amount of relativistic beaming that is occurring (see Chapter 3 and Chapter 7). The viewing angle, therefore, is very important in understanding the overall energetics of the jet. Often, determinations of the viewing angle will be coupled with determinations of the Lorentz factor Γ. This is the "bulk Lorentz factor" (rather than the Lorentz factor of the individual radiating particles), which comes from the speed at which the "blobs" or features in the jet are moving.

One determination of the angle (and in this case, Γ) was made by Scarpa and Urry (2001). They discussed the energy budget of the known optical jets, and found that the above parameters lay in a "most probable" region centered around $\Gamma \sim 7.5$ and $\theta \sim 20^\circ$. These values were reached by requiring the jets to transport enough kinetic energy to power an average radio lobe, since the kinetic power of the jet depends on Γ. The "most probable"

Name	Length (arcsec)	Length (kpc)
3C 15	4.2	5.3
3C 66B	8.0	3.2
3C 78	1.5	0.8
3C 120	15.0	24.8
PKS 0521−365	6.5	6.4
3C 200	0.8	3.6
3C 212	2.2*	12.5
3C 245	1.6*	9.1
3C 264	2.2	0.9
3C 273	23.0	56.2
M87	25.0	2.1
3C 346	3.6	9.0
3C 371	4.5	4.1
3C 380	1.4	8.5
PKS 2201+044	2.1	1.1

Table 2.3: Projected lengths of optical jets, in both arcseconds and kiloparsecs. The kiloparsec lengths are calculated using $H_0 = 75$ km s^{-1} Mpc^{-1}. Note that an * indicates that the length shown was calculated by the author from published images.

region was found by considering the amplification or de-amplification of the jet emission due to relativistic beaming (a de-amplified jet is less likely to be detected), which depends on both Γ and θ.

An alternative method is that used by Sparks et al. (2000). They imaged the nearest five 3CR galaxies that host optical jets, and found evidence for almost circular dust disks in four of them. They interpreted these disks as being face-on, so that the optical jets emerge close to perpendicular to these disks. From this, they find a critical line of sight angle of 30°– 40°, above which an optical jet is not seen. Taking the beam angular width to be $\sim 1/\Gamma$, this implies a minimum value of $\Gamma \sim 1.4 - 2$.

A somewhat different way of obtaining viewing angles for jets has been the approach of Ghisellini et al. (1993). They used observations of superluminal motion of radio jets to obtain an upper limit on the viewing angle. To do this, the Doppler factor δ needs to be found, and then the angle can be calculated from the apparent transverse speed β_a. The Doppler factor is calculated by comparing the predicted self-Compton flux at X-rays with that observed – this gives an expression for δ in terms of the radio and

X-ray fluxes, and the angular size of the radio core. The derived angles, for those sources with optical jets (only four of them have calculated values), are typically $\lesssim 10^\circ$ (although one source, 3C 345, has $\theta = 17^\circ$). We do note, however, that these Doppler factors are derived using non-simultaneous data, which may lead to erroneous results (particularly for the more variable sources).

Superluminal motion has also been observed in the optical for one optical jet – that of M87. Biretta et al. (1999) observed M87 with *HST* at five different epochs from 1994 to 1998, and found superluminal motion with apparent speeds from $4c$ to $6c$. For the fastest features, they find that the orientation angles must satisfy $\theta \lesssim 19^\circ$ and the Lorentz factors must be $\Gamma \gtrsim 6$ (with the sense that larger angles require larger Lorentz factors and produce smaller Doppler factors – an angle of $\theta = 19^\circ$ requires $\Gamma = 40$ and gives $\delta = 0.5$, compared with $\theta = 10^\circ$ requiring $\Gamma = 6$ and $\delta = 5.7$ (see Table 3 of Biretta et al. (1999))).

2.3 X-ray jets

Finally, we will move from the optical region to briefly discuss jets at X-ray energies. The two best-known optical jets, those of M87 and 3C 273, have both been detected in X-rays, as has a knot in the jet of 3C 120. The detection of the M87 jet was first reported by Schreier et al. (1982), based on observations with the *Einstein* satellite, and were further developed by Biretta et al. (1991). Due to the comparatively poor resolution of this satellite, the detection of the jet was dominated by the emission from the core and from the strongest of the emission knots. A similar detection was made with *ROSAT* (Neumann et al. 1997). The emission process may be synchrotron, although it is likely to be due to a different population of electrons to that emitting the radio–optical spectrum. Alternatively, it may be due to some other X-ray process (such as thermal bremsstrahlung or inverse Compton scattering) (Biretta et al. 1991; Meisenheimer et al. 1996).

The *ROSAT* satellite also detected X-ray emission from a radio knot in 3C 120 (Harris et al. 1998). Since this radio knot has not been detected at optical frequencies (the optical jet is much closer in to the core), it is unlikely that the X-ray emission is due to synchrotron. However, since no simple thermal bremsstrahlung or inverse Compton model fits the data, Harris et al. speculate on the existence of a separate, high-energy population of electrons that radiate a flat-spectrum X-ray component.

The launch last year of the *Chandra* X-ray Observatory provided a startling new example of an X-ray jet. The first target for the observatory was the radio quasar PKS 0637−752, a point source (so it was believed) that was to be used to calibrate the telescope optics. However, it was immediately apparent that there was an X-ray jet (Schwartz et al. 2000), which was coincident with the known radio jet (Tingay et al. 1998). At the source redshift of $z = 0.651$, the jet has a length of some 100kpc.

The origin of the X-rays is not certain (Chartas et al. 2000). A single-component power law synchrotron model does not work, as the optical emission is several orders of magnitude below the interpolation between the radio and X-ray data. Other models, such as inverse Compton, are difficult to fit effectively (Schwartz et al. 2000).

The jet of 3C 273 has also been imaged with *Chandra* (Marshall et al. 2000). Morphologically, the X-ray emission is strongest at the end of the jet closest to the core, and then decreases as the jet gets further away. This is the opposite sense to the radio emission, which is strongest at the head of the jet. The spectrum of the first knot in the jet (i.e. the one closest to the core) is consistent with a single power law extending from radio to X-ray energies, which may be due to synchrotron emission (although it is also possible that at least some of the X-ray emission originates from inverse-Compton scattering of the microwave background by relativistic motion in the jet). The likelihood of synchrotron emission being responsible for the X-ray flux decreases the further along the jet you go.