Chapter 7

THE RELATIVISTIC BEAMING HYPOTHESIS—ITS DOMAIN OF VALIDITY

In the introductory chapter, some of the successes of the relativistic beaming hypothesis and the unified interpretation that motivated this thesis were enumerated. Some further successes that were part of the thesis have been described in Chapters 4, 5 and 6. Clearly there is much appeal in the simplicity of the proposition, and it is important to examine its domain of validity. In this chapter, the evidence that has accumulated over the years in favour of the hypothesis, as also the counter-evidence, is summarized. Important disclaimers, possible future confrontations of the assumptions, and some speculations are enumerated.

7.1 Bulk relativistic motion in the nuclear regions of active galaxies

(a) Superluminal motion has been observed in about 23 radio sources (e.g., Zensus & Pearson, 1988), and provides the most direct evidence in support of bulk relativistic motion in the nuclear regions of these quasars. It is now widely accepted that the apparent speeds faster than light are due to bulk relativistic motion at small angles to the line of sight. Note that ~~superluminal~~ bulk relativistic motion in the nuclei of quasars accounts for (though is not proven by) the almost universal one-sidedness of the nuclear radio jets detected by VLBI.

(b) From angular sizes of the nuclear radio components (measured using VLBI) and the observed limits to the x-ray flux density, lower limits to the relativistic Doppler factors can be inferred, which imply bulk relativistic motion in several objects (Cohen, 1985).

(c) The severe problems that arise in the interpretation of the properties of BL Lacertids and Optically Violent Variables (viz., infrared luminosities in excess of the Eddington limit, the large magnetic fields required to prevent the (unobserved) excessive inverse Compton x-rays, etc.) are alleviated if it is assumed that bulk relativistic motion occurs in the nuclei of these objects (Impey, 1987).

(d) The form of the inverse correlation between measured internal proper motion of the superluminally moving components and redshift is consistent with the supposition that relativistic beaming is important in these objects (Cohen *et al.*, 1988).

7.2 Evidence for the unified interpretation

(a) High dynamic range radio imaging has shown that CDQs have outer components of similar nature to those of LDQs (Perley *et al.*, 1980; Browne *et al.*, 1982a).

(b) The prominence of the nuclear radio component of quasars inversely correlates with the projected linear size, and directly with the degree of misalignment of the radio structure away from collinearity (Kapahi & Saikia, 1982).

(c) The unified interpretation correctly predicts the proportions of flat and steep radio spectrum quasars in samples of radio sources selected at high radio frequencies (Orr & Browne, 1982). The Lorentz factors required are consistent with those derived from observed superluminal motion. The scheme also correctly predicts the form of the source counts of quasars with flat radio spectrum (Orr & Browne, 1982).

(d) If the position angle of the polarization of the radio nuclear component is used to infer the orientation of the nuclear-scale structures, it follows that degree of misalignment between radio structures on the nuclear scale and those on the large scale correlates with R (this thesis, chapter 5).

(e) When looked for, superluminal motion is detected in almost every CDQ, supporting the hypothesis that they are inclined at small angles to the line of sight (e.g., the inventory in Porcas, 1987; Schalinski *et al.*, 1988).

(f) The superluminal speeds that have been detected in sources with extended double structure (e.g., Zensus & Porcas, 1986; Hough, 1986) only serve to emphasize the ubiquity of bulk relativistic motion in quasars. There are already suggestions of a correlation of the measured value of $\beta_{\mathrm{apparent}}$ with R where β is the apparent ratio of the measured velocity to the velocity of light (Browne, 1987).

(g) The redshift distributions and source counts of quasars with steep and flat radio spectrum in high frequency radio surveys are consistent with the unified scheme of Orr & Browne (1982) (Kapahi & Kulkarni, 1986; Morisawa & Takahara, 1987).

(h) For steep and flat spectrum quasars that are intrinsically similar in the scheme of Orr & Browne (1982), the redshift distributions are similar (Kapahi & Kulkarni, private communication), implying that they occur in the same volume, as indeed would be expected in the unified scheme.

7.3 Evidence for relativistic motion in the kiloparsec-scale jets

(a) Both nuclear (VLBI-scale) jets and the larger kiloparsec-scale jets are mostly one-sided in quasars. In every quasar with a large scale jet, a nuclear jet, when looked for, has been found, and it always points towards the base of the large scale jet. This argues for a common cause of asymmetry on both scales. The case for "Doppler favouritism" in nuclear jets is compelling, and thus at least mild bulk relativistic motion must occur on the large scale too (Scheuer, 1987).

(b) The detectability of large scale jets appears to increase with the prominence of the radio nuclear component (Saikia, 1984b; Bridle, 1986).

(c) The kiloparsec-scale (one-sided) jets detected in the quasars from the D2 sample preferentially point towards the outer component with the brighter hot spot, which is consistent with bulk relativistic motion on a large scale and mild relativistic motion in the hot spots (this thesis, chapter 4).

(d) Quasars with relatively large surface brightness ratios for the outermost hot spots tend to have higher values of R, consistent with the contention that they are likely to be oriented closer to the line of sight (this thesis, chapter 4).

(e) High resolution dual-frequency polarimetry of 23 quasars has shown that the "jet side" of the nucleus of radio quasars depolarizes less rapidly with wavelength than the opposite side (Laing, 1988; Garrington *et al.*, 1988). The depolarization is almost certainly due to differential Faraday rotation, and does not correlate with the size or brightness of the components. In the case of the radio galaxy Cygnus A (Dreher *et al.*, 1987), the depolarization has been established as due to Faraday rotation by a foreground screen (as opposed to being internal). Extrapolating this fact to the case of quasars implies that the "jet side" is seen through less of the foreground screen and is therefore the approaching side, which is consistent with the idea that the jets are relativistically beamed.

7.4 Aspect dependence at other emission wavelengths ?

If the relativistic beaming hypothesis and the unified interpretation are assumed to be valid, then consistency with the data demands that emission at other wavelengths is aspect dependent also. These cases are summarized below.

(a) The Highly optically Polarized Quasars (polarization > 3%) and BL Lacertids show a correlation between the prominence of the radio core component and the r.m.s. scatter in the optical polarization, implying that a significant fraction of the optical continuum is aspect-dependent (Wardle *et al.*, 1984). Further, this correlation would be expected if the emission is synchrotron radiation produced in a relativistic jet. The weak evidence for quasars with a "preferred position angle" of the optical polarization to exhibit relatively prominent extended radio structure is also consistent with this "optical relativistic jet" hypothesis (Wardle *et al.*, 1984; Blandford & Königl, 1979).

(b) Sets of quasars with steep radio spectrum that are chosen to be intrinsically similar (in the unified scheme of Orr & Browne, 1982) to those with flat radio spectrum appear optically fainter than the latter, which requires that the optical continuum be aspect dependent in the same sense as the radio emission is (Browne & Wright, 1985).

(c) The prominence of the radio nuclear component correlates with the apparent optical brightness of the nucleus (this thesis, chapter 6), consistent with the suggestion of Browne & Wright (1985) that the optical continuum may be aspect dependent.

(d) The ratio of the optical luminosity of the nucleus to that of the host galaxy in radio quasars correlates with the prominence of the nuclear radio component (this thesis, chapter 6), again supporting the above.

(e) The Baldwin effect (anti-correlation of equivalent width of the CIV emission line with optical continuum luminosity) may be understood if the optical continuum is assumed to arise from a thin and opaque disc (Netzer, 1985).

(f) The widths of the broad emission lines in quasars inversely correlate with R (Wills & Browne, 1986; Wills & Wills, 1986). This can be understood if the motion of the gas emitting the lines is confined to a plane perpendicular to the radio ejection axis, perhaps in the form of a disc.

(g) The degree of optical polarization of quasars correlates with R, which can be understood if the optical emission is of synchrotron origin and is relativistically beamed (Wills *et al.*, 1988).

(h) The equivalent width of the narrow O[III]5007 emission line and broad MgII line inversely correlates with R. This can be understood if the optical continuum is aspect dependent and the luminosity of the emission line is independent of aspect (Wills & Browne, 1986; Browne & Murphy, 1987).

(i) The rest equivalent width of the CIV absorption doublets observed within $\pm$ 5000 km s^{-1} of the emission line redshift inversely correlates with both the flatness of the radio spectrum and the optical luminosity (Foltz *et al.*, 1987). The above result suggests that firstly, the absorbing clouds are within the host galaxy of the quasar (as opposed to being associated with the cluster containing the quasar, cf. Foltz *et al.*, 1987) since the anti-correlation is with an intrinsic property of the quasar, viz., R. Secondly, the anti-correlations, if interpreted in the relativistic beaming scenario, suggest that the distribution of the absorbing clouds is not isotropic about the nucleus of the quasar, but lie preferentially along a plane perpendicular to the radio axis.

(j) The curve correlating the x-ray luminosity with nuclear radio luminosity is steeper for CDQs than for LDQs. This is consistent with the suggestion that part of the x-ray emission is aspect-dependent (Browne & Murphy, 1987).

(k) From soft x-ray (2-3.5 keV) spectra of 33 quasars observed on-axis with the IPC of the Einstein satellite, Wilkes & Elvis (1987) have reported a correlation between the flatness of the x-ray spectral index and radio loudness. The attempt to reconcile their results with the earlier HEAO 1(2-10 keV) results led them to conclude that in all quasars is present a x-ray component that obeys a flat power law, and that this component preferentially dominates radio loud quasars above ~0.5keV.

It turns out that for the set of 18 radio quasars from Wilkes & Elvis (1987), the CDQs tend to have systematically flatter soft x-ray spectral indices than the LDQs. (Fig. 7.1 shows the distribution of soft x-ray spectral index, α_E for the radio loud quasars from the sample bifurcated at R = 0.5.) It is thus suggested that there is marginal evidence for the flat x-ray component being aspect-dependent.

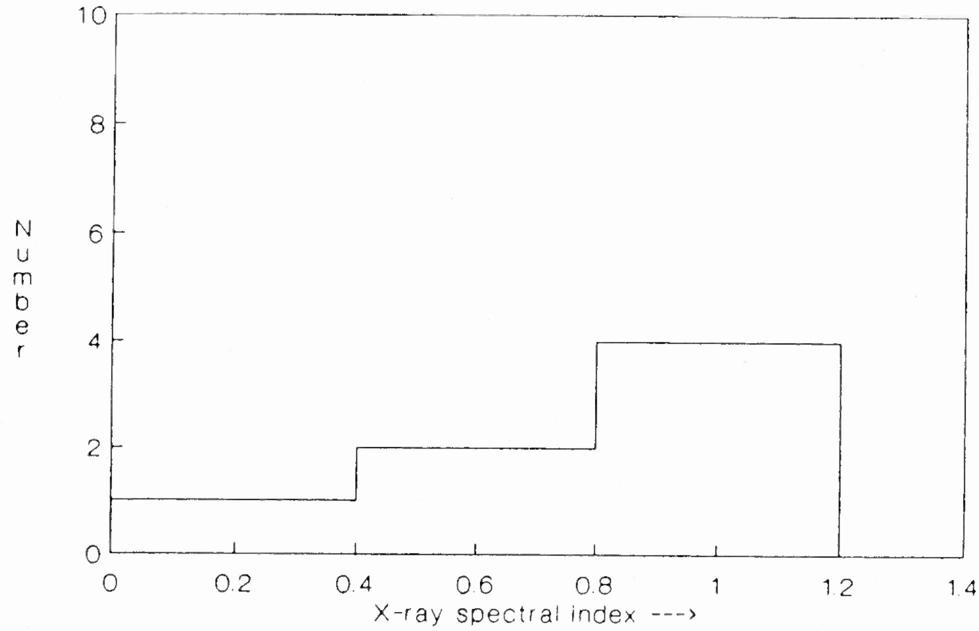

Fig.7.1a Quasars with R < 0.5

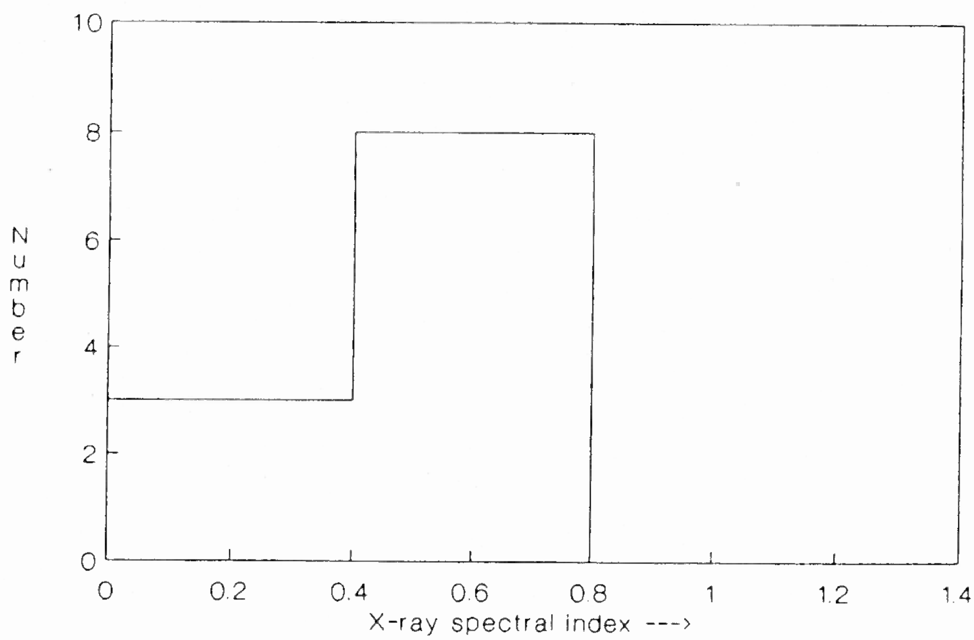

Fig.7.1b Quasars with R > 0.5

7.5 Disclaimers

(a) Radio-quiet quasars are probably a physically different population from the radio-loud ones (Peacock *et al.*, 1986) and tend not to inhabit elliptical galaxies the way the latter do (e.g., Fried, 1986). Thus they clearly cannot be co-opted into the unified interpretation of Blandford & Königl (1979) for radio loud quasars. Further, it is unlikely that this unified interpretation applies to them as an independent class. However, perhaps a unified scheme akin to that of Scheuer & Readhead (1979) is valid, wherein the total radio power (as opposed to primarily the nuclear power) is relativistically beamed, and the objects inclined close to the line of sight are the really "radio silent" quasars (this thesis, Section 6.9.4).

To the extent that the two populations of quasars *do* share some common properties at optical, ultraviolet and infrared wavelengths, it is to be expected that radio-quiet quasars would *appear* similar to CDQs in some respects. Several of the properties of radio-quiet quasars are better studied for the brighter objects, and, given that the optical nuclei of radio-quiet quasars are similar to the radio loud ones, this bias implies a selection effect in favour of more face-on nuclear discs. For instance, radio quiet quasars resemble CDQs both in their Broad Emission Lines (Heckman, 1980; Steiner, 1981), and in Broad Absorption Line properties (e.g., Foltz *et al.*, 1987).

(b) Compact Steep Spectrum quasars are probably seats of intense interaction of the radio jets with the interstellar medium of the host galaxy (van Breugel *et al.*, 1984a; van Breugel *et al.*, 1988). While their radio nuclei are often prominent (this thesis, chapter 4), VLBI mapping has shown that the nuclei exhibit complex structures (Fanti *et al.*, 1988; Nan *et al.*, 1988). Thus while the data do not preclude relativistic motions, the parameter R is clearly not a good measure of the angle of inclination to the line of sight in these objects.

7.6 Disbelief

Several bits of evidence have been cited to argue against relativistic beaming on both small and large scales, and also against the validity of the unified interpretation for radio quasars. They are discussed below.

(a) Heckman (1983) argues that while the unified interpretation requires that CDQs do not differ from LDQs in their emission line properties, they actually do differ in two respects. Firstly, the broad emission lines are wider and more complex in the LDQs. Secondly, the FeII multiplets are weaker in the LDQs. The author further argues that the narrower Broad Emission Lines in CDQs cannot be a mere orientation effect since they are similar to those of the radio-quiet quasars, which are claimed to be viewed from a random direction.

However, in view of the arguments of Section 7.5, it is not at all clear that a bias towards optically brighter radio-quiet quasars for determination of line profiles would not bias the orientation of the radio-quiet sample. Indeed, Wills & Browne (1986) have shown that the data for CDQs and LDQs are consistent with an orientation effect. Further, Wills & Browne suggest that the FeII lines appear weaker in LDQs at least partly because the lines blend with each other due to their larger apparent width, leading to an underestimate of their strength. They suggest that in any case the trend may be with line width rather than R, and therefore does not contradict the unified scheme.

(b) Wardle & Potash (1984) use jet-counterjet ratios derived for the eight largest (angular size) quasars of the 4C sample to argue that Doppler effects alone cannot account for the one-sidedness in these quasars. "The only assumption" they make is that extended quasars in the 4C catalogue are randomly oriented with respect to the line of sight. But it has been argued in Chapter 6 (Section 6.3) that samples of radio sources selected at low frequencies, if not completely identified, could be significantly biased with respect to orientation. Thus the value of 4.1 that Wardle & Potash derive for a maximum possible jet-counterjet asymmetry due to Doppler effects is likely to be an underestimate.

(c) Lonsdale (1986) has argued that the radio structural properties of distant quasars cast "serious shadow" over the relativistic beaming hypothesis. The 23 quasars which do show jets (out of a total of 72 quasars of high redshift and steep radio spectrum), are claimed to not show any of the correlations expected in the relativistic beaming scenario. This is despite the fact that the 23 quasars form a sample of objects "mostly close to the line of sight" (if beaming occurs), and therefore "should be most sensitive to orientation effects".

It should be noted, however, that on a large scale, only mild relativistic beaming is required for the generally observed jet asymmetries to be *statistically* consistent with the relativistic beaming hypothesis. Moreover, ultra-dissipative jets *are* known in quasars (e.g., Saikia, 1984b), and so a sample selected by the presence of large scale jets is not necessarily one with objects mostly close to the line of sight. Further, the sample derives from steep radio spectrum quasars, which would have relatively weaker nuclear components, and would therefore be relatively closer to the plane of the sky. Indeed, the range of values of R in the sample of Lonsdale (1986) reflects mostly intermediate orientations. Ultra-dissipative jets may well contribute to the correlation of jet prominence with jet curvature. But given the limited range in R in the sample, it *does* correlate with jet curvature, source size and jet prominence in the sense expected from the beaming hypothesis. The exception is in the region of $R < 0.1$, where there are only two objects. Before absence of evidence is taken as evidence of absence, even if only for distant quasars, the correlations need to be examined for a larger range of R. Also, if the jets are ultra-dissipative, they would not be expected to point towards the side with the brighter hot spot, and this needs to be verified.

(d) De Ruiter *et al.* (1986) and Padrielli *et al.* (1988b) use properties of quasars from the "complete" Bologna (B2) sample to argue that the relativistic beaming hypothesis is not sustained. De Ruiter *et al.* (1986) assert that the deviation of the R-distribution of the B2 sample from that for the 3CR sample contradicts unified scheme. But it has been demonstrated in this thesis (Section 6.3) that the B2 sample is biased, and a selection effect accounts for the apparent inconsistency.

Padrielli *et al.* (1988b) show that none of the quasars in the sample with misaligned radio structure are of flat radio spectrum, which again contradicts the relativistic beaming hypothesis wherein flat radio spectrum sources are at small inclinations to the line of sight and therefore small intrinsic misalignments would be preferentially amplified. But in their sample, there are actually a total of 20 objects of flat radio spectrum, of which as many as 10 are unresolved, and are therefore excluded from the misalignment analysis. It is these objects that are most likely to show non-collinearity, as these authors themselves have demonstrated (misalignment correlates inversely with angular size). Further, among the quasars with steep radio spectrum, at least 9 are likely to turn out to be Compact Steep Spectrum quasars, of which 4 are bent. The unified scheme clearly does not apply to these objects, where there is likely to be a large contribution to the distortions from interaction with the interstellar medium.

7.7 Persisting embarrassments

Even though a cogent argument can be put forth in favour of the relativistic beaming hypothesis and the unified interpretation for radio quasars, there still remain puzzles that cast doubt on the scenario.

(a) Superluminal quasars appear to be too large (e.g., de Bruyn & Schilizzi, 1983; Browne, 1987). If superluminal quasars are inclined at small angles to the line of sight, then their observed sizes are foreshortened by large projection factors, and if deprojected, they appear far larger than their counterparts that are supposedly closer to the plane of the sky.

Quantification of the degree of the problem is tricky, since the deprojection factors in each case are elusive: it is possible that VLBI observes (superluminal motion of) the shocked pattern, which can have a different speed from the underlying (relativistic) flow that causes the nuclear radio flux density to be boosted; intrinsic misalignments of the jets further confuse the issue (Browne, 1987). The latter author argues for a correlation of intrinsic linear size with Lorentz factor as a resolution of the question. Also, the possibility that some quasars might masquerade as powerful radio galaxies, e.g., Broad Line Radio Galaxies, needs to be looked into, especially given the possibility that aspect dependent obscuration of the central nucleus might be occurring (e.g., Netzer, 1987; Thompson *et al.*, 1988).

(b) The host galaxies of CDQs appear to be different from those of LDQs. The latter appear to be more luminous in the O[III] emission line (Boroson *et al.*, 1985; Stockton & MacKenty, 1987). This observation contradicts the supposition that differences between the two classes are due to orientation effects alone. However, the possibility that the result is merely due to a correlation between luminosity of the O[III] emission and intrinsic (unbeamed) radio power needs to be investigated (this thesis, Section 6.9.2).

7.8 Future confrontations of assumptions, and some speculations

Adopting the view that the relativistic beaming hypothesis and the unified-interpretation-approach promises significant order and progress in the search for a unified phenomenology for active galactic nuclei, some tests of the ideas involved are proposed.

(a) How are the magnetic fields oriented in the nuclear jets of LDQs? In Chapter 5 of this thesis, where the orientation of the core polarization was used to infer the orientation of the nuclear jet, an important assumption was made, *viz.*, that the magnetic field is predominantly *along the nuclear jet.* But if the CDQs *do* intrinsically differ from the LDQs (for instance, if the nuclei of LDQs are intrinsically less luminous) then it might be expected that the magnetic field structuring would be complex/different. On kiloparsec scales, it is known that for jets emanating from powerful cores, the projected magnetic field is parallel to the jet all along, whereas those from weak cores do have "perpendicular" projected magnetic field configurations. Verification of the premise is therefore an important step. It may be done using VLB Interferometric mapping (that would give the jet orientation) and VLA polarimetric imaging of the central components (for the magnetic field orientation) of LDQs (at a frequency $\geq$ 5 GHz, so as to able to ignore Faraday rotation effects). Currently improved VLBI sensitivities make the mapping of LDQs feasible. Further, constraints need to be placed on the nuclear jet-counter-jet asymmetry, so that the study of the relationship of this asymmetry to the polarization properties of the (unresolved) nuclear jet may be made.

(b) Is the "blue bump" in the spectra of quasars aspect dependent? This bump has been suggested to be thermal emission from an accretion disc (e.g., Edelson & Malkan, 1986). It is important to investigate the extent to which orientation effects due to this disc play a significant role in the observed optical continuum. Determination of the relative prominence of the "blue bump" for a sample of quasars with a range of R values using spectrophotometry would be interesting in this regard. Since the amount of emission observed from a thin opaque disc would be most sensitive to aspect near edge-on inclinations of the disc, in the relativistic beaming framework, these inclinations would correspond to values of $R < 1$.

(c) Is part of the x-ray continuum aspect-dependent? It is important to our interpretation of the x-ray emission from quasars to determine the role of aspect in their apparent properties. To confirm or refute the suggested dependence of a component of the x-ray continuum on inclination (Section 7.4) x-ray colours of quasars with a range of inclinations need to be determined. The commissioning of telescopes such as the Röntgen satellite and AXAF in the future, make such experiments feasible.

(d) Are the host galaxies of LDQs different from those of CDQs? This question (cf., Section 7.5) needs to be investigated in detail by choosing for the comparison CDQs and LDQs that are *predicted to be intrinsically similar* by the scheme, and by excluding the Compact Steep Spectrum quasars. The possibility that the observed correlation of O[III] luminosity with radio spectrum being simply because more (intrinsically) radio luminous objects are more "O[III] luminous" needs to be tested.

(e) Are there any quasars masquerading as radio galaxies? Quasars with "edge-on" accretion discs may have their optical nuclei further (preferentially) dimmed if there exists surrounding dust that is also confined to a plane parallel to the disc. This possibility needs to be investigated, especially in the light of what was summarized in Section 7.7.

(f) Are the motions of Broad Absorption Line clouds confined to a plane? Given that the radio emission offers a handle on the orientation of the quasar, this needs to be used to explore in detail the possibility that the absorption clouds may perhaps have their motions confined to a plane perpendicular to the radio axis.

CONCLUSIONS

The main conclusions of this thesis are enumerated below.

(1) The parameter R is a reasonably good statistical measure of the angle of inclination to the line of sight in radio quasars, except when they are of the Compact Steep Spectrum kind, where interaction of the radio jet with the interstellar medium is important (Chapter 4).

(2) A sample of quasars of suspected one-sided radio structure was imaged with high angular resolution. The results show that (a) the radio jets almost always point towards the side with the brighter hot spot, consistent with them being at least mildly relativistically beamed, and (b) quasars with relatively larger asymmetry in surface brightness of the outer hot spots have more prominent nuclear radio components, suggesting that they are at preferentially smaller inclinations to the line of sight (Chapter 4).

(3) High angular resolution polarimetry of the nuclear radio components of quasars shows that there appear to be large misalignments between the orientation of the nuclear jets and the overall radio axis for the core-dominated quasars, while lobe dominated quasars show more collinear structures. This is consistent with the unified scheme (Chapter 5).

(4) Several properties of the optical emission from quasars require that if the radio emission is relativistically beamed, then the beaming is accompanied by an enhancement of the optical continuum. The prominence of the nuclear radio component correlates with the apparent optical brightness and the ratio of the

nuclear to host galaxy emission (Chapter 6).

(5) Components moving with bulk relativistic speeds, as well as thermal emission from a thin and opaque disc appear to contribute to the optical continuum. The latter component would enhance the scatter in the Hubble diagram of quasars with steep radio spectrum (Chapter 6).

(6) While the radio-quiet quasars cannot be co-opted into unified scheme, nor can the scheme be applied to them as an independent class, an alternative unified scenario akin to that of Scheuer & Readhead (1979) appears to apply to them (Chapter 6).

(7) Core-dominated quasars appear to have preferentially flatter spectral indices for the soft x-ray emission relative to lobe-dominated quasars, suggesting that part of the x-ray continuum is aspect-dependent (Chapter 7).

(8) The relatively large sizes of "superluminal quasars" and the apparently higher luminosity of the O[III] emission line from the host galaxies of lobe-dominated quasars are persisting embarrassments to the relativistic beaming hypothesis and the unified scheme, and need to be further explored.

(9) In conclusion, several of the observed properties of radio quasars can be understood if relativistic beaming of the radio emission is invoked. Given this hypothesis, observations imply that emission from quasars at other wavelengths may also be aspect-dependent. The appeal of the hypothesis and the unified interpretation is not in consistency or otherwise with rigourous statistics. It lies primarily in its simplicity and simultaneous ability to explain a melange of phenomena using what is essentially one mechanism.

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