Misaligned radio quasars

V. K. Kapahi

Tata Institute of Fundamental Research, Poona University Campus, Ganeshkhind, Pune 411 007, India

The extended lobes in a small fraction of radio quasars show a pronounced departure from collinearity with the central nucleus. A careful analysis using new and existing aperture synthesis observations of high angular resolution and dynamic range shows no significant increase in these misalignments or 'bends' with cosmic epoch up to redshifts of about 2, contrary to claims in the literature. It is also argued that in many cases the bends may be largely apparent, small true misalignments between the parsec-scale and kiloparsec-scale jets being amplified by the close orientation of quasar jets with our viewing directions.

ALTHOUGH the twin lobes of radio quasars are generally well aligned on either side of the central nucleus, suggesting a high degree of symmetry and collimation in the central engine, mapping of large quasar samples has revealed many examples[1,2] in which the hotspots in the lobes depart significantly from collinearity with the nucleus. The study of such misalignments can in principle be used to infer their physical causes and to probe the environment of radio quasars. From an investigation of the epoch dependence of source morphology, Miley[3] and Barthel and Miley[4] have reported that radio quasars at $z > 1.5$ appear to be much more bent and distorted than those at $z < 1.5$. This has been interpreted by them as arising mainly from the interaction of radio jets with a clumpier ambient medium at earlier epochs. In view of the considerable cosmological significance of this result it is important to be sure that observational and instrumental effects are not responsible for introducing an epoch dependence of radio structures. Ideally, quasars at different redshifts must be mapped with similar dynamic range and number of resolution elements across their total extent. Barthel and Miley[4] (hereafter BM) compared the structures in a sample of 80 steep-spectrum quasars at $z > 1.5$, which were mapped[2] with a resolution of ~ 0.4 arcsec and a dynamic range generally better than 200:1, with a lower redshift sample compiled from the literature to have similar radio luminosities and spectral indices. As the median redshifts in the two groups differ by a factor of ~ 2.5, and the median value of the largest angular size (LAS) goes approximately as z^{-1} (e.g. ref. 5), a typical resolution of ~ 1 arcsec is desirable for the low-z group. The structural data for about half of the 40 extended sources in this group were, however, derived by BM from maps of poorer resolution and/or rather limited dynamic range.

In order to enlarge the comparison sample of $z < 1.5$ quasars and to obtain higher quality data, I have recently mapped 46 objects using the National Radio Astronomy Obsevatory's Very Large Array (VLA) in the US at a wavelength of 6 cm. Using this new data as well as other data in the literature, I present here the results of a new analysis of the epoch dependence of source distortions that does not appear to support the BM result. I argue, furthermore, that in many cases a substantial part of the observed bending at all redshifts could be only apparent, a small degree of true misalignment being amplified by the close alignment of the jet axes in quasars with our viewing direction[6]. This possibility has been ignored[7] or considered unimportant[4] in some earlier discussions of the causes of bent structures among quasars.

Observations and results

The sample of quasars with $z < 1.5$ observed with VLA included objects from the BM list as well as all those picked from a recent compilation of extended quasars[8] to have a 408 MHz flux density > 2 Jy, but without adequate maps in the literature. In order to ensure the similarity of the low- and high-redshift samples with regard to their total radio luminosity and spectral indices, the available radio spectral information on the objects was carefully examined and only those with $P_{5\,\mathrm{GHz}} > 10^{26}$ WHz^{-1} (for $H_0 = 75$ km sec^{-1} Mpc^{-1} and $q_0 = 0.5$) and steep high-frequency spectral indices $\alpha_{2.7}^{10.7} \geq 0.6$ ($S_\nu \propto \nu^{-\alpha}$) were included to conform to the criteria used by BM to define the low-z sample. The observations were made in the 'B' configuration of VLA in the form of two 'snapshots' at different hour angles for each source. Ten of the sources with LAS > 50 arcsec were also observed at 20 cm. The data were processed at Socorro using the standard AIPS software. The final images have angular resolutions of ~ 1.4 and ~ 4 arcsec at 6 and 20 cm respectively, and a dynamic range of about 200–1000:1. The maps, and a detailed discussion of the observed structures will be presented elsewhere (Kapahi, in preparation).

The higher brightness sensitivity and dynamic range of the present observations are clearly apparent in the greater detail and complexity seen in the lobes of many sources, compared to their earlier maps. Two examples are shown in Figure 1. In the case of 1012+022 (Figure

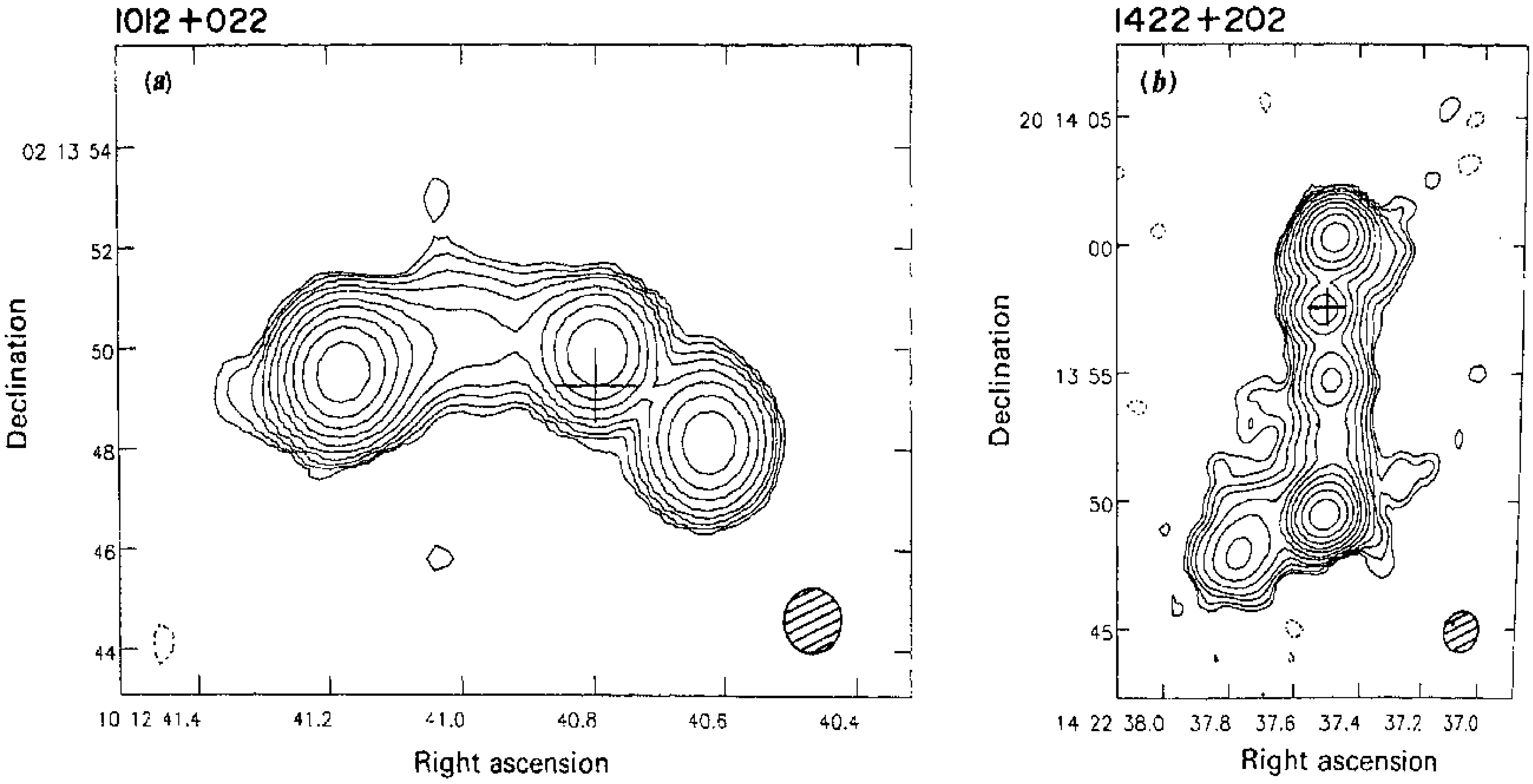

Figure 1. Total intensity maps of (a) 1012+022 and (b) 1422+202 at 4.9 GHz. Contour levels are 0.3 × [−1, 1, 1.5, 2.5, 4, 8, 16, 32, 64, 128, 256 and 512] mJy/beam. Optical positions of quasars are shown by crosses.

1a) the bent structure did not show up in the earlier model[9] based on fitting limited visibility data. The source 1422+202 (Figure 1b) was previously known[10] to have a simple triple structure in the north–south direction. Note that, although the strongest peaks of emission on the two sides are aligned with the core, the previously unknown structure to the south–east makes this source appear distorted. This raises an important question concerning a quantitative measure of misalignment. The misalignment angle, β, was defined in BM as the supplement (misprinted as 'complement') of the angle between the lines from the peaks in the source *extremities* to the radio core ($\beta=0°$ for a collinear source). It is not always obvious as to which feature in the brightness distribution should be regarded as the extremity. In the high-z sample a few quasars have been assigned large values of β in BM because of fainter features in one of the lobes extending at large angles from the axis defined by the brightest peaks (e.g. 1323+655 and 1540+180 in ref. 2), not unlike the case for 1422+202. Such a measure of bending is clearly sensitive to the brightness limit and dynamic range of the observations. Some examples of basically similar structure in low-z quasars are 0300–004, 0610+260, 1606+180 (present observations), 3C 249.1, 3C 334 and 3C 351 (high-dynamic-range VLA maps[11]; D. H. Hough, private communication). Such features could be the fossil radiation due to a change in the direction of the beam or may be related to the phenomenon of flow redirection[12] subsequent to the collision of a beam with a dense intergalactic cloud. In the following discussion I will use values of β estimated from the peaks of surface brightness in the two lobes, which should correspond in most cases to hotspots where the beams are presently depositing their contents.

The plot of β vs z is shown in Figure 2. Apart from the 46 sources reported here, it includes another 73 sources with $z<1.5$ (from ref. 8) that satisfy the luminosity and spectral-index criteria of BM and for which reliable estimates of β could be made from data in the literature. Some relevant data on the most 'crooked' quasars ($\beta>20°$) are listed in Table 1. The data for the $z>1.5$ quasars in Figure 2 are taken from BM, with some changes due to the different definition used here, which results in a significantly lower β for three sources (viz. 1323+655, 1345+584 and 1540+180) and a higher value for one source (0553−205). There is no evidence in Figure 2 for an increase in β with z over the entire range of redshift, contrary to the BM result. The fraction of sources with large bends ($\beta \geqslant 20°$) does not also appear to increase with redshift at least up to $z \sim 2$ (~22% for $z<1$ and 19% for $1<z<2$). It rises to

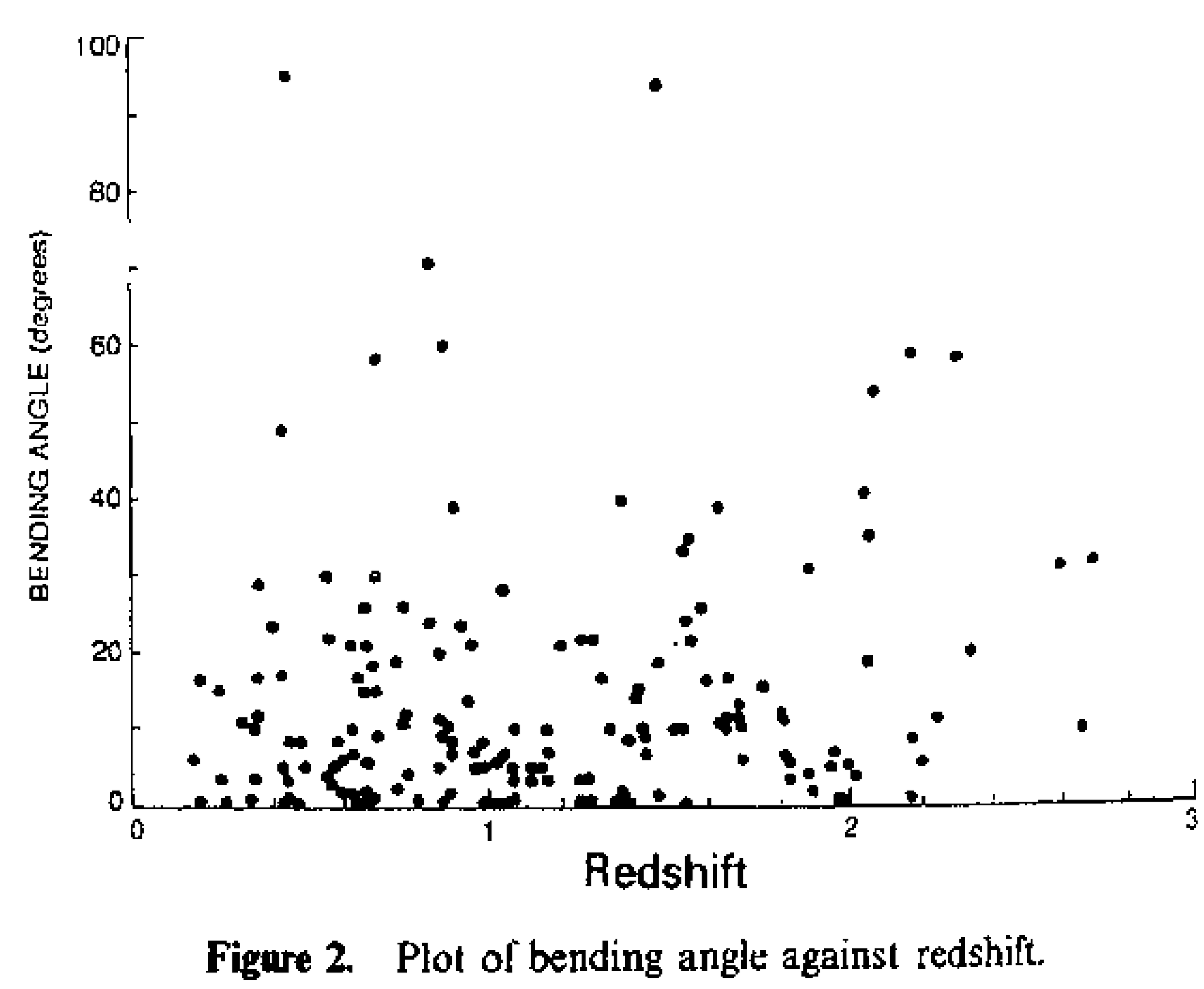

Figure 2. Plot of bending angle against redshift.

Table 1. Misaligned quasars ($\beta > 20°$) at $z < 1.5$.

Quasar	z	LAS (sec)	β (deg)	Ref.
0127+233	1.470	3	94	28
0159−117	0.669	15	21	p
0736−019	1.033	9	28	p, 13
0758+143	1.197	4	21	28
0812+020	0.402	19	23	p
0903+169	0.411	43	49	29
0957+003	0.907	31	23	p
1012+022	1.374	9	40	p
1118+128	0.685	22	30	30
1132+303	0.614	15	21	31
1136−135	0.554	16	30	31
1241+166	0.557	15	22	32
1244+324	0.949	23	21	29
1253+104	0.824	25	24	30
1415+172	0.821	7	71	30
1423+242	0.649	22	26	p
1458+718	0.904	2	39	28
1530+137	0.771	12	26	p
1628+363	1.254	16	22	1
1741+279	0.372	9	29	31
1828+487	0.691	3	58	28
2112+172	0.878	7	60	30
2140+102	1.280	12	22	1
2305+187	0.313	7	95	18

p = Present work, (Kapahi, in preparation).

~47% for $z > 2$, but the number of sources involved is too small to allow one to decide if this is significant. Although some previous studies[1,13] did not also find a correlation between β and z up to redshifts of about 2, these did not exclude the core-dominated quasars, as was done by BM and in the present work. It appears then that bending does not depend strongly on z even if only the lobe-dominated objects are considered. It should also be noted that the slightly different definition of β used by BM compared to the present and previous studies should also have little effect on this conclusion, because, as already pointed out, several quasars at both low and high redshifts would acquire higher values of β if measured from the source 'extremities'.

The absence of any significant epoch-dependent bending is in contrast to the behaviour of another well-studied aspect of the radio structure, viz. the maximum linear size of the radio source estimated from the separation of hotspots in opposite lobes. Linear sizes are known to decrease rapidly with increasing redshift for both quasars[4] and radio galaxies[14]. This evolution in linear sizes has generally been attributed to increasing density of the intergalactic medium and the shrinking size of the interface between galactic haloes and the intergalactic medium through which the radio jets have to propagate outwards[15]. The lack of any strong epoch dependence for quasar alignments reported above and the similar conclusion in the case of radio galaxies[16] suggest that, even though the density enhancements (with either a uniform or a clumpy distribution) may be quite effective in slowing down the passage of the advancing hotspots, they are unlikely to be more effective in deflecting the radio jets. It is possible, as discussed in the next section, that a majority of the observed misalignments originate close to the central engine, well within the passage of the jets through the interstellar medium of the host galaxies.

What causes the bending?

Several physical causes have been suggested to explain the misaligned structures. These include motion of the quasar in a cluster of galaxies[17], changes in the direction of the rotation axis of the central engine[18], and deflection of radio beams by interaction with interstellar or intergalactic gas clouds[4,7]. It is possible that some of these are responsible for the distortions in different sources. An examination of the radio maps shows that a majority of the structures appear to be consistent with the bends occurring close to the core; only a minority show signs of bends in jets on the scale of tens of kpc. It is therefore also possible that much of the observed bending is only apparent[6,19]; smaller true misalignments (of up to 10 to 15°) between the pc- and kpc-scale jets, either intrinsic to the ejection mechanism or resulting from one of the causes mentioned above, may be appearing magnified due to the small angles between the jet axes and our lines of sight. This would also explain, in a natural way, the observed correlation between bending and dominance of the radio core[6,20,21] as well as the inverse correlation between bending and projected linear sizes[1,6,20,21]. Relativistic beaming effects in the approaching jet would then be responsible for the core dominance and the geometrical foreshortening would make the bent sources appear smaller.

It can be argued[4], however, that projection effects should be unimportant in the present study as the quasars considered here were chosen to have steep spectral indices (hence relatively weak radio cores of flat spectrum) that should discriminate against strong Doppler boosting and small viewing angles. It is worth noting, nevertheless, that in the 'unified scheme' for quasars (ref. 22) the apparent dominance of the core depends on several parameters, such as the Lorentz factor in the nuclear jets (Γ), the ratio of core to extended flux density when viewed normal to the jet axis ($R_{\perp}$), and the relative spectral indices of the core and lobe emission. Although, for viewing angles small enough to cause a significant magnification of the intrinsic bend angle (viewing angles smaller than ~20° are necessary to make a true bend of 10° appear as $\beta > 30°$), typical values of these parameters should in most cases cause a quasar to have a dominant core (and an overall spectral index $\alpha < 0.6$), it is possible that because of the likely spread in the values of the above-mentioned parameters, some sources can be viewed at sufficiently small angles to appear highly misaligned, without the cores becoming dominant. Some evidence in support of this possibility is provided by the observation that misaligned structures are much more common among core-dominated quasars. In the compilation of extended quasars[8] with $\alpha > 0.5$ between 0.4 GHz and 5 GHz, from which the present sample of $z < 1.5$ quasars was drawn, there are 23 objects with a well-determined bending angle, but were not included in Figure 2 only because of a high-frequency spectral index $\alpha_{10\,\mathrm{GHz}}^{2.7\,\mathrm{GHz}} < 0.6$. As many as 13 (57%) of these strong-core sources have $\beta > 20°$. The fraction of such sources appears to be even higher (14 out of 23, i.e. 61%) among the strongly core-dominated sources selected by flux at 5 GHz, that have been found from very-high-dynamic-range mapping to have extended structure on both sides of the core[23]. The corresponding fraction of bent sources in the lobe-dominated quasars at $z < 2$ studied here is only 20%.

A potentially serious problem with invoking projection effects is the very low probability of small viewing angles. In a randomly oriented sample, only 6% of the sources would be viewed within 20° of their axes, not enough to explain the distribution of β if the intrinsic bends are only of the order of 10°. Two different factors can, however, lead to an increase in the probability. First, the presence of true bends increases the range of angles somewhat because close alignment with either of the two jet directions can now result in amplification. Second, and more importantly, the jet axes may not be randomly oriented even in samples of steep-spectrum radio quasars. It has been pointed out[24,25] that optically magnitude-limited samples of radio quasars are likely to be biased towards small viewing angles because of the aspect dependence of the optical continuum radiation. This bias may well be important to the quasars investigated here because most of them come from such samples.

It has also been suggested recently[26] that all quasars (whether lobe-dominated or core-dominated) are inclined at small angles ($\lesssim 45°$) to the line of sight; those close to the plane of the sky have their active nuclei and broad line region hidden from our view by an obscuring torus and get classified as radio galaxies. This unification of quasars and radio galaxies is consistent with a variety of observations[26,16] although some problems remain to be sorted out[16,27]. It is interesting to note in this connection that a comparison of the present quasar sample with a sample of 3CR radio galaxies up to $z = 1.8$ shows[16] galaxies to have significantly less bent structures, with no galaxy having a bend angle in excess of about 20°. This is consistent with the idea that radio galaxies and quasars differ only with regard to orientation and that projection effects make quasars appear more bent. Alternatively, galaxies and quasars must either have intrinsically different ejection mechanisms, or the jets must encounter intrinsically different environments.

1. Hintzen, P., Ulvestad, J. and Owen, F., *Astron. J.*, 1983, **88**, 709.
2. Barthel, P. D., Miley, G. K., Schilizzi, R. T. and Lonsdale, C. J., *Astron. Astrophys. Suppl. Ser.*, 1988, **73**, 515.
3. Miley, G. K., in *Observational Cosmology* (IAU Symp. No. 124) (eds. Hewitt, A., Burbidge, G. and Fang, L. Z.), D. Reidel, Dordrecht, 1987, p. 267.
4. Barthel, P. D. and Miley, G. K., *Nature*, 1988, **333**, 319.
5. Kapahi, V. K., in *Observational Cosmology* (IAU Symp. No. 124) (eds. Hewitt, A., Burbidge, G. and Fang, L. Z.), D. Reidel, Dordrecht, 1987, p. 252.
6. Kapahi, V. K. and Saikia, D. J., *J. Astrophys. Astron.*, 1982, **3**, 465.
7. Stocke, J. T., Burns, J. O. and Christiansen, W. A., *Astrophys. J.*, 1985, **299**, 799.
8. Singal, A. K., *Mon. Not. R. Astron. Soc.*, 1988, **233**, 87.
9. Wills, D., *Astrophys. J. Suppl.*, 1979, **39**, 291.
10. Potash, R. I. and Wardle, J. F. C., *Astron. J.*, 1979, **84**, 707.
11. Hough, D. H., Bridle, A. H., Burns, J. O. and Laing, R. A., *Bull. Am. Astron. Soc.*, 1988, **20**, 734.
12. Lonsdale, C. J. and Barthel, P. D., *Astron. J.*, 1986, **92**, 12.
13. Neff, S. G., Hutchings, J. B. and Gower, A. C., *Astron. J.*, 1989, **97**, 1291.
14. Kapahi, V. K., *Astron. J.*, 1989, **97**, 1.
15. Gopal-Krishna and Wiita, P. J., *Mon. Not. R. Astron. Soc.*, 1987, **226**, 531.
16. Kapahi, V. K., in *Parsec-scale Radio Jets* (eds. A. Zensus and T. Pearson), Cambridge Univ. Press, 1990, p. 304.
17. Hintzen, P. and Scott, J. S., *Astrophys. J.*, 1978, **224**, L47.
18. Gower, A. C. and Hutchings, J. B., *Astrophys. J.*, 1982, **253**, L1.
19. Readhead, A. C. S., Cohen, M. H., Pearson, T. J. and Wilkinson, P. N., *Nature*, 1978, **276**, 768.
20. Saikia, D. J., in *Extragalactic Energetic Sources* (ed. Kapahi, V. K.), Indian Academy of Sciences, Bangalore, 1985, p. 105.
21. Hough, D. H. and Readhead, A. C. S., *Astron. J.*, 1989, **98**, 1208.
22. Orr, M. J. L. and Browne, I. W. A., *Mon. Not. R. Astron. Soc.*, 1982, **200**, 1067.
23. Murphy, D. W., Ph.D. thesis, 1988, University of Manchester.
24. Kapahi, V. K. and Shastri, P., *Mon. Not. R. Astron. Soc.*, 1987, **224**, 17.
25. Kapahi, V. K., Subrahmanya, C. R. and De Silva, S., in *Active Galactic Nuclei*, (IAU Symp. 134) (eds. Osterbrock, D. E. and Miller, J. S.), Kluwer Academic, Dordrecht, 1989, p. 531.
26. Barthel, P. D., *Astrophys. J.*, 1989, **336**, 606.
27. Jackson, N. and Browne, I. W. A., *Nature*, 1990, **343**, 43.
28. Pearson, T. J., Perley, R. A. and Readhead, A. C. S., *Astron. J.*, 1985, **90**, 738.
29. Swarup, G., Sinha, R. P. and Hilldrup, K., *Mon. Not. R. Astron. Soc.*, 1984, **208**, 813.
30. Hutchings, J. B., Price, R. and Gower, A. C., *Astrophys. J.*, 1988, **329**, 122.
31. Shastri, P., Ph.D. thesis, 1990, University of Bombay.
32. Kapahi, V. K. and Hough, D. H., 1990, in preparation.

ACKNOWLEDGEMENTS. National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with National Science Foundation. I thank D. H. Hough and D. W. Murphy for useful discussions and for making data available before publication. Most of this work was done while the author held a National Research Council Senior Research Associateship at the Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, USA.

17 May 1990; revised 4 June 1990