The inevitable youthfulness of known high-redshift radio galaxies

Katherine M. Blundell & Steve Rawlings

University of Oxford, Astrophysics, Keble Road, Oxford, OX1 3RH

Some galaxies are very luminous in the radio part of the spectrum. These 'radio-galaxies' have extensive (hundreds of kiloparsecs) lobes of emission powered by plasma jets originating at a central black hole.[1] Some radio-galaxies can be seen at very high redshifts,[2] where in principle they can serve as probes of the early evolution of the Universe. Here we show that for any model of radio-galaxy evolution in which the luminosity decreases with time after an initial rapid increase (that is, essentially all reasonable models[3]), all observable high-redshift radio-galaxies must be seen when the lobes are less than 10^7 years old. This means that high-redshift radio galaxies can be used as a high-time-resolution probe of evolution in the early Universe. Moreover, this result explains many observed trends of radio-galaxy properties with redshift,[4-9] without needing to invoke explanations based on cosmology[10] or strong evolution of the surrounding intergalactic medium with cosmic time,[6] thereby avoiding conflict with current theories of structure formation.[11]

The luminosity P of the expanding lobes of a classical double radio galaxy with age t depends on the bulk kinetic power delivered by the jets Q. It will also be influenced by its environment, which we parameterize at radius r as $n(r) \propto r^{-\beta}$, where $n(r)$ is the number density of gas particles. A good empirical fit to radial density profiles[12,13] is obtained using $\beta = 1.5$. It is also a reasonable approximation to the so-called 'universal' density profile which emerges from N-body simulations of structure formation.[14] We normalise the density profile by consideration of (i) detections of thermal X-ray haloes,[15] (ii) weak and strong gravitational lensing,[16,17] (iii) galaxy counting,[18] and (iv) studies of radio depolarisation,[8] obtaining a characteristic number density n_{100} at radius 100 kpc of $n_{100} = 2 \times 10^3 \, \mathrm{m}^{-3}$. Falle[19] found the length of a radio-galaxy D grows as

$$D \propto \left(\frac{t^3 Q}{n_{100}} \right)^{\frac{1}{5-\beta}}. \qquad (1)$$

A simple model for a radio-source's luminosity evolution assumes that Q remains constant as t increases. Combining equation (1) with a minimum-energy estimate of the energy stored in the lobes leads to:

$$P \propto Q^{(26-7\beta)/[4(5-\beta)]} n_{100}^{9/[4(5-\beta)]} t^{(8-7\beta)/[4(5-\beta)]}. \qquad (2)$$

Using $\beta = 1.5$ gives

$$P \propto Q^{31/28} n_{100}^{9/14} t^{-5/28}. \qquad (3)$$

Equations (1) and (2) can be used to produce evolutionary tracks of P versus D for radio-sources of given Q and n_{100} (Fig. 1a). A model[20] which incorporates synchrotron cooling, adiabatic expansion losses and inverse Compton scattering off the cosmic microwave background modifies these tracks slightly (Fig. 1a) and at large D introduces downward curvature.

Our study of the properties and dependencies of complete samples[7] of radio-sources led us to a model which includes the rôle of the hotspots (the compact, high surface-brightness regions at the end of jets) in *(i)* governing the energy distribution of the particles injected into the lobes and *(ii)* promoting increasing expansion losses throughout a radio-galaxy's life. In this model the P–D tracks are, for a given environment, steeper (see Fig. 1b) than for the models in Fig. 1a. After a very rapid initial increase, the luminosity of the radio lobes will *decrease* as the source grows, for $\beta \gtrsim 0.3$ in the case of the last model (Fig. 1b), and for $\beta > 8/7$ in the case of the first and second models (described by equation (2) and ref 20 respectively) (Fig. 1a). With $\beta \sim 1.5$ radio luminosity inevitably declines with t.

Application of a low-frequency flux-limit will inevitably lead to more distant sources selected by the survey being more radio luminous (this is called the Malmquist bias). From equation 2, this means that the most distant objects in a survey are drawn from a higher-Q population. Since the dependence of P on Q is stronger than on n_{100}, and since the dynamic range in Q is larger than that of n_{100}, jet-power Q is the dominant factor, though density n_{100} may be an important source of subtle biases. If, as we have argued, the luminosities of radio-sources decrease as they age, more distant sources fall through the flux-limit sooner than low-redshift sources. Since our light-cone intercepts a radio-source at a random point in its life-time,[7] it is only the high-redshift radio-sources which are intercepted by our light-cone when they are *young* and luminous which can be selected by these surveys. *Any model involving a declining luminosity-evolution will give a 'youth-redshift degeneracy'.* Although it has been demonstrated that the low-frequency surveys[21] are unlikely to be much affected by surface-brightness dimming, any effect will be in the sense to make old radio-galaxies at high-z even harder to detect.

The youth-redshift degeneracy is highly relevant to our

understanding of the alignment effect,[4] the optical and infra-red light which is aligned along radio-jet axes. Where this is caused by star-formation, it will be more easily triggered close into the host galaxy or within the product of a recent merger (assuming this is the jet-triggering event[22]) than at distances further out sampled by the head of an expanding radio-source later in its lifetime. Where this is caused by dust-scattered quasar light, the certain youthfulness of distant radio-galaxies alleviates the near discrepancy[23] between radio-source ages and the time-scale for which dust grains can survive in the presence of shocks caused by the advancing radio-jets. The 'youth–redshift degeneracy' is consistent with the finding that the smallest sources in a sample of $z \sim 1$ radio-galaxies (all with very similar luminosities) are those which are most aligned with optical emission.[24] Indeed, Best et al.[24] remarked that the sequence of changing optical aligned structure with increasing radio size could be naturally interpreted by comparing it with different phases of the interaction of the radio jets with the interstellar and intergalactic medium as the radio-sources age.

Barthel and Miley[6] had suggested that higher redshift environments are denser and inhomogeneous than at low redshift since they found increased distortion in the structures of their high-z sample of steep-spectrum quasars compared with their low-z sample. Sources which are younger may have the passage of their jets considerably more disrupted where there is a higher density and greater inhomogeneity in the ambient post-recent-merger environment. A general trend of denser inter-galactic environments at high-z cannot be inferred from their result.

The mild linear size evolution observed in low-frequency selected samples of classical double radio-sources[5–7] arises because the high–z sources are younger, hence tend to be shorter. It is the positive dependence on jet-power of the rate at which the lobe-lengths grow (equation 1) which contributes to the linear size evolution being as mild as it is.[7] Since we find it unavoidable that objects found at high-redshift will be younger than those at low redshift, the use of classical double radio sources as 'standardizable' rods[10] is beyond reach. Fig. 2 illustrates the difficulty of distinguishing between different underlying cosmic geometries when more dramatic influences, such as the youth-redshift degeneracy, and variations in source environments, are at work. Garrington & Conway[8] have found a tendency for depolarisation to be higher in sources with a higher P and/or z. Objects with higher P or z which are younger will be in much more recently merged environments with the consequence that inhomogeneities in density or magnetic field will more readily depolarise the synchrotron radiation from the lobes, in addition to being closer in to the centre of the potential well.

Many of the highest–z radio-galaxies have gas masses comparable to gas-rich spiral galaxies,[9] and inferred star-formation rates which, in the local Universe, are rivalled only by galaxy-galaxy mergers like Arp 220.[25] If high-z objects are being viewed during a similar merging of sub-components the associated star formation could be responsible for a significant fraction of the stellar mass in the remnant galaxy. Since we have shown (Fig 1) that the high–z radio-galaxies — those detected by SCUBA — are necessarily young ($\lesssim 10^7$ years), and since the whole merger must take a few dynamical crossing times, or 10^{8-9} years, the implication is that the event which triggered the jet-producing central engine is synchronised with massive star formation in a gas-rich system, perhaps as material streams towards the minimum of the gravitational potential well of the merging system. The youth-redshift degeneracy may explain why few lower-z radio-galaxies show similarly large (rest-frame) far-infrared luminosities compared to the high-z population: they are being observed significantly longer after the jet-triggering event.

The dramatic decrease in the co-moving space density[26] of radio-galaxies from $z \sim 2$ to the local Universe is most likely to be explained by the probability of suitable jet-triggering events like galaxy-galaxy mergers[22] being much lower now than at earlier cosmic epochs. Cygnus A is a local example demonstrating that this probability is not yet zero. Since efficacious interactions and mergers require slow relative motions,[27] rich galaxy groups are excellent sites for jet-triggering events by virtue of their high galaxy number density but low velocity dispersion prior to virialisation. This is evinced by studies of the dynamics of rich groups containing luminous quasars[28] which find anomalously low velocity dispersions for systems of high galaxy number density. But if systems, whose galaxy number densities are sufficiently high that galaxy encounters are frequent, have formed into large virialised clusters by $z \sim 0$ then the galaxies' encounter velocities will be prohibitively high. This explains why radio-source environments may be seen to get richer between $z \sim 0$ and $z \sim 0.5$.[29,18] The space density evolution of radio-sources may therefore be understood in the context of current structure-formation theories.[11] Only in systems where the merger of sub-groups is still on-going are jets likely to be triggered in the local Universe: Cygnus A was recently shown to be embedded in an ongoing merger of two sub-clusters.[30,31]

Fig. 2 shows the location on the P–D plane of the most extreme redshift ($z > 3$) radio galaxies known. Fig. 2a ($\Omega_M = 1$, $\Omega_\Lambda = 0$) (Ω_M and Ω_Λ are the dimensionless density parameters for matter and the cosmological constant respectively) suggests that not only are the extreme redshift sources younger than the most distant objects in the 3C sample[32] but that they have similar jet-powers. Fig. 2b ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) requires that objects with higher jet-powers ($\sim 10^{40}$ W) exist beyond those detected in the $z < 2$ Universe sampled by 3C. The extreme values of Q required in even the most conservative cosmological model constrains their jet-producing AGNs to be only those with the most massive black holes. A jet-power of 10^{40} W corresponds to a 100%-efficient Eddington-rate process for a 10^9 $M_\odot$ black hole. Unless one is prepared to postulate significantly larger black hole masses, it seems difficult to avoid the conclusion that by focussing on these objects, we are selecting objects from the extreme end of the distribution function of black-hole masses. Interpretation of the properties of distant radio galaxies must account for this effect alongside the youth-redshift degeneracy. We remark that the term 'Cosmological evolution' should not be used to describe trends with redshift where they arise because of well-understood physical mechanisms. The youth-redshift

degeneracy is one example where trends with source age have become confused with changes with cosmic epoch. However, the youth-redshift degeneracy brings two important benefits: first, since extreme-redshift radio galaxies are young, all with similar Q, they deliver the fine time-resolution required for the solution of problems which it may be difficult to study with objects like optically-selected quasars, whose ages are indeterminate: examination of the environments of distant radio galaxies provides a snapshot of the host galaxy evolutionary status just after the jet-triggering event. Second, at redshift ~ 4 we observe radio galaxies ~ 1 Gyr after the Big Bang and in environments which saw a jet-triggering event a time-step no greater than 10^7 years prior to that. This time-step is over an order of magnitude smaller than the dynamical crossing time of a massive galaxy, and 2 orders of magnitude smaller than the age of the Universe at the epochs probed, giving fine time-resolution essential to any study of triggering (and hence merging) rates at early cosmic epochs.

Received 11 December 1998; Accepted 13 March 1999.

1. Begelman, M. C., Blandford, R. D. & Rees, M. J. Theory of extragalactic radio sources, *Rev. Mod. Phys* **56**, 255–351 (1984).

2. Rawlings, S., Lacy, M., Blundell, K. M., Eales, S. A., Bunker, A. J. & Garrington, S. T. A radio galaxy at redshift 4.41, *Nature* **383**, 502–505 (1996).

3. Baldwin, J. E. in *Extragalactic radio sources* (eds Heeschen, D. S. & Wade, C. M.) 21–24 (Proc. of the 97 IAU Symp. Reidel, Dordrecht, 1982).

4. McCarthy, P. J., van Breugel, W., Spinrad, H. & Djorgovski, S. A correlation between the radio and optical morphologies of distant 3CR radio galaxies, *Astrophys. J.* **321**, L29–L33 (1987).

5. Kapahi, V. K., Subrahmanya, C. R. & Kulkarni, V. K. On the interpretation of the observed angular-size–flux-density relation for extra-galactic radio sources, *J. Astrophys Astron.* **8**, 33–50 (1987).

6. Barthel, P. D. & Miley, G. K. Evolution of radio structure in quasars: a new probe of protogalaxies?, *Nature* **333**, 319–325 (1988).

7. Blundell, K. M., Rawlings, S. & Willott, C. J. The nature and evolution of classical double radio sources from complete samples, *Astronom. J.* **117**, 677–706 (1999).

8. Garrington, S. T. & Conway, R. G. The interpretation of asymmetric depolarization in extragalactic radio sources, *Mon. Not. Roy. Astr. Soc.* **250**, 198–208 (1991).

9. Hughes, D. H., Dunlop, J. S., Archibald, E. N., Rawlings, S. & Eales, S. A. in *Cosmological evolution of the submillimetre luminosity of high-redshift radio galaxies in* The birth of galaxies (ed Guiderdoni, B.) in press (Frontieres, Paris, 1998).

10. Daly, R. A. Cosmology with powerful extended radio sources, *Astrophys. J.* **426**, 38–50 (1994).

11. Eke, V. R., Cole, S. & Frenk, C. S. Cluster evolution as a diagnostic for Ω, *Mon. Not. Roy. Astr. Soc.* **282**, 263–280 (1996).

12. Reynolds, C. S. & Fabian, A. C. ROSAT PSPC observations of Cygnus A: X-ray spectra of the cooling flow and hotspots, *Mon. Not. Roy. Astr. Soc.* **278**, 479–487 (1996).

13. Neumann, D. M. 3C 295, a cluster and its cooling flow at $z = 0.46$, *Astrophys. J.* **520**, astro–ph/9902035 (1999).

14. Navarro, J. F., Frenk, C. S. & White, S. D. M. A universal density profile from hierarchical clustering, *Astrophys. J.* **490**, 493–508 (1997).

15. Crawford, C. S. & Fabian, A. C. ROSAT observations of distant 3CR radio galaxies – II, *Mon. Not. Roy. Astr. Soc.* **282**, 1483–1488 (1996).

16. Bower, R. G. & Smail, I. A weak lensing survey in the fields of $z \sim 1$ luminous radio sources, *Mon. Not. Roy. Astr. Soc.* **290**, 292–302 (1997).

17. Deltorn, J. M., Fevre, O. L., Crampton, D. & Dickinson, M. A massive cluster of galaxies at $z = 0.996$, *Astrophys. J.* **483**, L21–L24 (1997).

18. Hill, G. J. & Lilly, S. J. A change in the cluster environments of radio galaxies with cosmic epoch, *Astrophys. J.* **367**, 1–18 (1991).

19. Falle, S. A. E. G. Self-similar jets, *Mon. Not. Roy. Astr. Soc.* **250**, 581–596 (1991).

20. Kaiser, C. R., Dennett-Thorpe, J. & Alexander, P. Evolutionary tracks of FRII sources through the P-D diagram, *Mon. Not. Roy. Astr. Soc.* **292**, 723–732 (1997).

21. Riley, J. M. Bright sources selected at 151 MHz – I. Some observations and identifications, *Mon. Not. Roy. Astr. Soc.* **238**, 1055–1075 (1989).

22. Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G. & Scoville, N. Z. Ultraluminous infrared galaxies and the origin of quasars, *Astrophys. J.* **325**, 74–91 (1988).

23. De Young, D. S. The 'alignment effect' and the evolution of dust in high-redshift radio galaxies, *Astrophys. J.* **507**, 161–172 (1998).

24. Best, P. N., Longair, M. S. & Röttgering, H. J. A. Evolution of the aligned structures in $z \sim 1$ radio galaxies, *Mon. Not. Roy. Astr. Soc.* **280**, 9L–12L (1996).

25. Genzel, R., Lutz, D. & Tacconi, L. Star formation triggered by galaxy collisions, *Nature* **395**, 859–862 (1998).

26. Longair, M. S. On the interpretation of radio source counts, *Mon. Not. Roy. Astr. Soc.* **133**, 421–436 (1966).

27. Aarseth, S. J. & Fall, A. M. Cosmological N-body simulations of galaxy merging, *Astrophys. J.* **236**, 43–57 (1980).

28. Ellingson, E., Green, R. F. & Yee, H. Y. C. Clusters of galaxies associated with quasars II: galaxy cluster dynamics, *Astrophys. J.* **378**, 476–486 (1991).

29. Prestage, R. M. & Peacock, J. A. The cluster environments of powerful radio galaxies, *Mon. Not. Roy. Astr. Soc.* **230**, 131–160 (1988).

30. Owen, F. N., Ledlow, M. J., Morrison, G. E. & Hill, J. M. The cluster of galaxies surrounding Cygnus A, *Astrophys. J.* **488**, L15–L18 (1997).

31. Markevitch, M., Sarazin, C. L. & Vikhlinin, A. Physics of merging clusters Cygnus A, A3667 and A2065, *Astrophys. J.* **521**, astro–ph/9812005 (1999).

32. Laing, R. A., Riley, J. M. & Longair, M. S. Bright sources at 178 MHz: flux densities, optical identifications and the cosmological evolution of powerful radio galaxies, *Mon. Not. Roy. Astr. Soc.* **204**, 151–187 (1983).
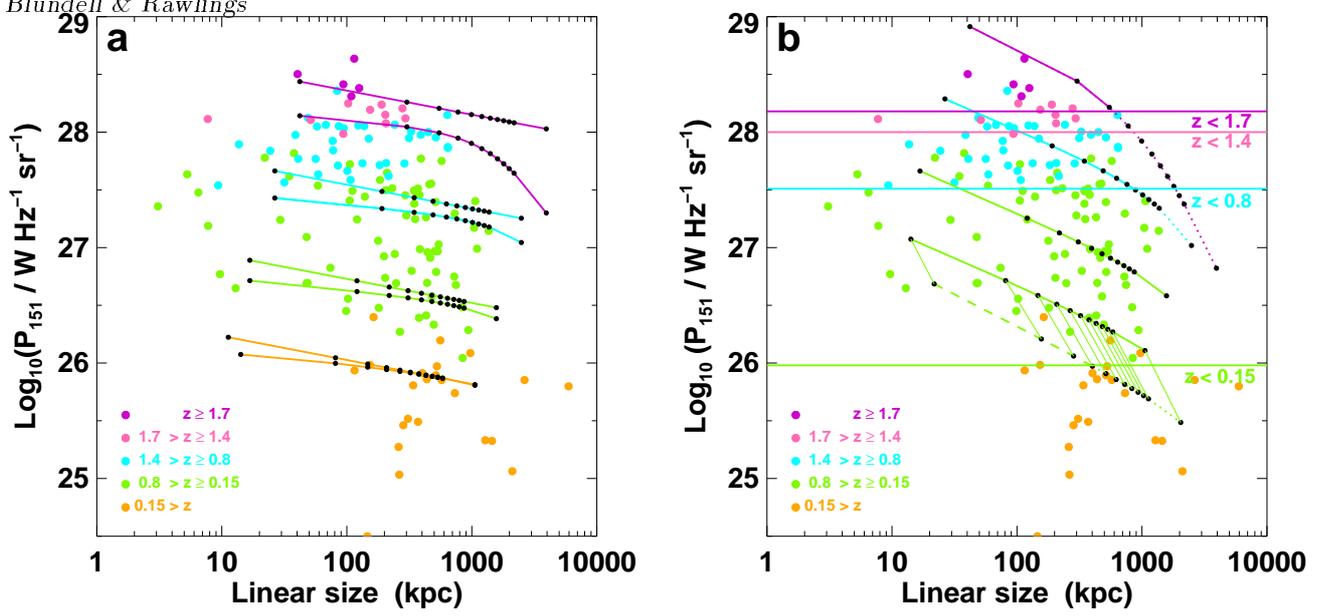
Figure 1 These plots show luminosity at rest-frame 151 MHz versus linear size. The tracks were generated assuming linear size growth according to the prescription of ref. 19. Small dots lie on all tracks to indicate the (rest-frame) ages $0.1, 1, 10, 20 \ldots 100, 200$ Myr. The jet-powers and redshifts are given by: *(upper to lower)* $Q = 5 \times 10^{39}$ W at $z = 2$, $Q = 1 \times 10^{39}$ W at $z = 0.8$, $Q = 2 \times 10^{38}$ W at $z = 0.5$ and $Q = 5 \times 10^{37}$ W at $z = 0.15$. The large coloured circles show the rest-frame luminosities at 151 MHz of members of the 3C sample[32] against their projected linear sizes. **a:** The luminosity development of an individual source is described by Equation 3 (straight tracks) and by the model of ref. 20 (curved tracks). **b:** These tracks were generated assuming the model for the luminosity evolution wherein the hotspot acts as a governor of the energy distribution to the radio lobes, developed in ref. 7. The solid lines of the tracks become dotted when the luminosity and redshift of that source are such that they fall below the survey flux-limit of 12 Jy. The uppermost horizontal line indicates that if a source of that luminosity is to make it above the flux-limit at 151 MHz of the 3C sample (12 Jy) then it must be at a redshift closer than 1.7; the corresponding lines at lower luminosities are for the lower redshifts 1.4, 0.8 and 0.15 respectively. The assumed environmental parameters are $n_{100} = 2 \times 10^3 \, \mathrm{m}^{-3}$ and $\beta = 1.5$ outside a core radius $a_\circ$ of 10 kpc, and $\beta = 1$ inside; the normalising constant[20] c_1 for Equation 1 is 3.5. $H_\circ = 50 \, \mathrm{km \, s}^{-1} \, \mathrm{Mpc}^{-1}$, $\Omega_M = 1$ and $\Omega_\Lambda = 0$. The dashed line in Fig 1b indicates how the lower track luminosity reduces by $\lesssim$ half an order of magnitude if the ambient density (hence n_{100}) becomes an order of magnitude lower.
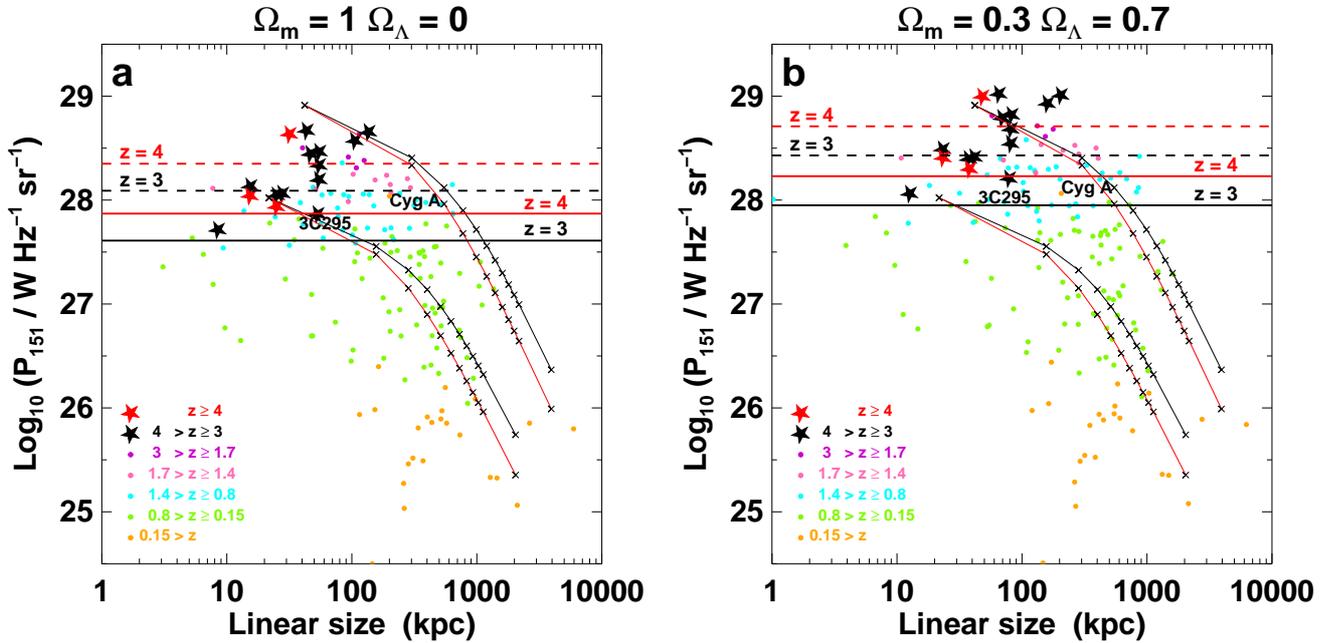
Figure 2 Tracks generated according to the same model as Fig. 1b, with parameters as in Fig. 1a; the coloured circles have the same meaning as in Fig. 1. The black stars represent the known radio-galaxies with $3 < z < 4$ and the red stars are those with $z > 4$. The dashed horizontal lines indicate the luminosity a source must have if it is to make it above a flux-limit at 151 MHz of 3 Jy at $z = 4$ (red) and $z = 3$ (black). The solid horizontal lines are for a flux-limit of 1 Jy. Cygnus A and 3C295 are indicated. The upper pair of tracks have $Q = 5 \times 10^{39}$ W and the lower pair have $Q = 5 \times 10^{38}$ W; the red tracks are for sources at $z = 4$ and the black tracks are for $z = 3$. Higher jet-powers must be invoked if $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ than if $\Omega_M = 1$ and $\Omega_\Lambda = 0$.