EVOLUTIONARY TRACKS OF EXTENDED RADIO SOURCES

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We know almost nothing about the evolutionary tracks of extragalactic radio sources but those tracks are, however, strongly constrained by the distribution of sources in the radio luminosity, P, overall physical size, D, diagram. This is the radioastronomer's H-R diagram, an analogy which two lines of algebra shows is exact. Fig. 1 is the P-D diagram for the 3CR 166 source sample of Jenkins et al. (1977) with later additions. Most of the sources are identified and have known redshifts. It is a flux density limited sample so that the numbers at any P are weighted relative to the true space density by $P^{3/2}$ because of the differing volumes of space sampled. The important feature of the diagram is the lack of sources greater than 1 Mpc in size. Because of doubts about the completeness of the sample in this region, we have made searches in the 6C 151MHz survey for sources having surface brightnesses lying between the two lines of slope 2 on the right of Fig.1. The numbers found to a limiting flux density of 1-2 Jy suggest that there is no serious underestimate of the numbers in the 166 source sample.

Interpretation of the diagram is helped by the reasonable assumption that sources expand and their lifetimes are $\ll H_o^{-1}$, which I think is true for all except the lowest P sources. The P-D diagram then reflects a steady state in which the density of points is, among other factors, $\propto$(velocity of expansion, $V)^{-1}$. If we adopt the simple view that the evolutionary tracks of all sources have the same shape, some tracks can be excluded. For example, P and V both constant leads to numbers of sources in successive decades in D in the ratio 1:10:100:1000, which is evidently untrue. To proceed further we need a physical model of radio sources and the only quantitative ones we have are those of Scheuer (1974). In his model A, two beams of constant cone angle impact on a uniform intergalactic medium giving hotspots in which particles are accelerated and then escape to fill a cigar-shaped bridge. The velocity of outward motion of the hotspots, $V \propto D^{-1}$ whilst the radio luminosity of the bridge, $P \propto D^{7/8}$. This model is a very bad fit to the points in Fig.1 because it gives a strong piling up of powerful, large sources. A cut-off in numbers at large sizes requires the sources to die rapidly so that we rarely see them dying; only two sources with $P > 10^{26}$ show

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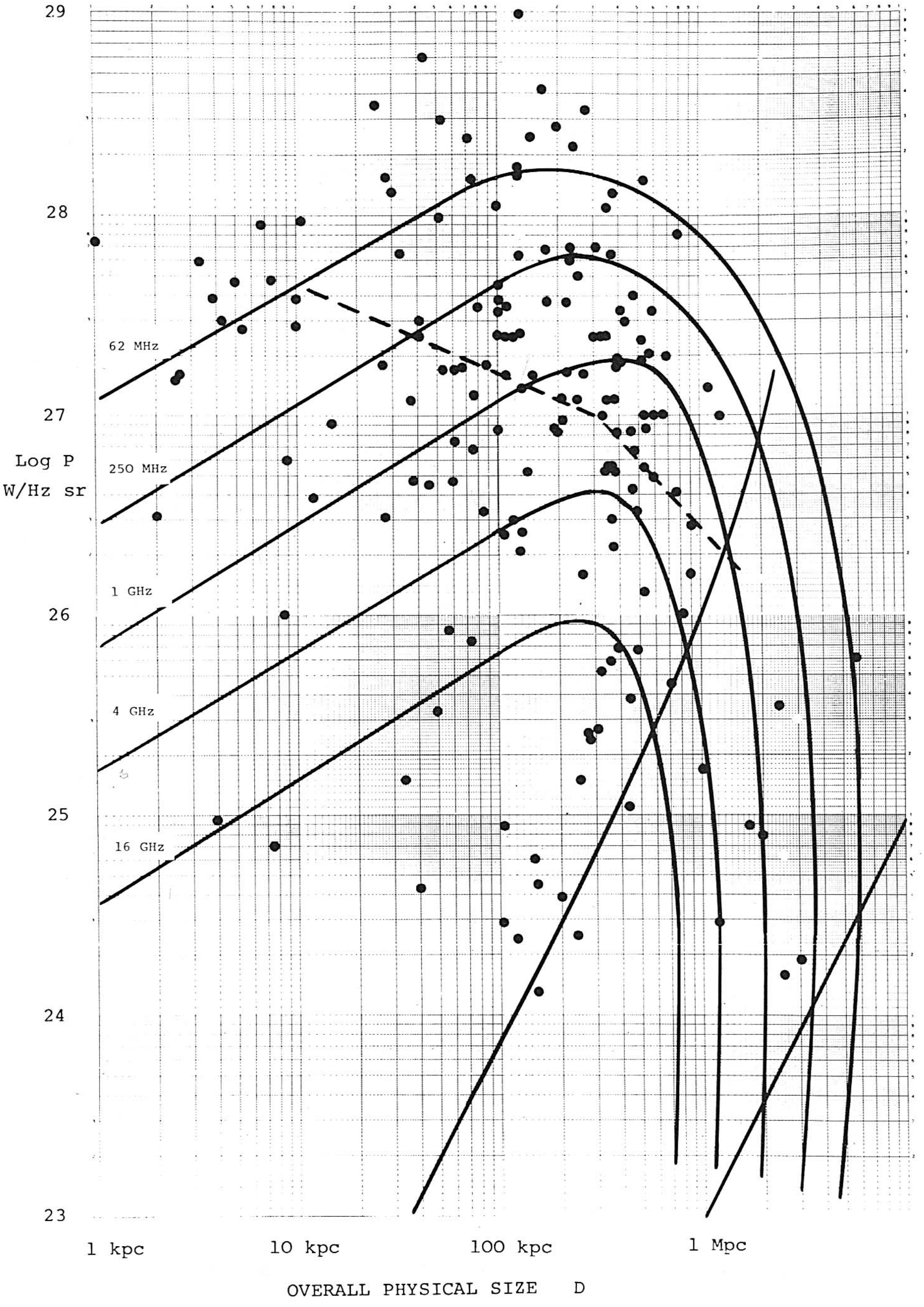

Fig 1. The P-D diagram for the 3CR 166+ sample.
Dashed line: Evolutionary track of a typical source.
Full lines : Surface brightness limits in 6C search.
Full curves: Synchrotron cut-off frequencies half way to hotspots.

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no hotspots. It turns out to be difficult to kill them quickly enough; switching off the beams and allowing adiabatic expansion to take its toll is too slow.

So Scheuer's models need modification and there is one change which we know we ought to make. He took a uniform external medium purely for algebraic reasons and in the absence of other information. We now know from Xray observations that galaxies may have their own gaseous haloes and more extended atmospheres associated with a cluster. All models, and those Xray observations which have been reduced, show the density, ρ, falling increasingly steeply with radius. Scheuer's model is easily calculable for a power law variation of ρ and the corresponding dependence on D of P, V and the number, N, of sources in the P-D diagram per unit interval of log D is:

$$\rho \propto R^{\alpha} \; ; \quad P \propto D^{(14+11\alpha)/16} \; ; \quad V \propto D^{-(1+\alpha/2)} \; ; \quad N \propto D^{(106+49\alpha)/32} \; .$$

In Fig.1, N increases slowly with D up to sizes of $\sim$ 300 kpc and thereafter falls rapidly. Using the density of points to deduce the best-fitting power law variation of ρ with R gives $\alpha = -1.9$ (10 kpc < D < 300 kpc) and $\alpha = -2.9$ (D > 300 kpc), values which are a good approximation to the density variation in an isothermal galactic atmosphere, with a radial scale similar to that of the Xray observations of M87 (see Fig.2). The shape of the corresponding evolutionary track is shown as the dashed line in Fig.1. The main conclusion from this analysis is that Scheuer's models still give a good account of the behaviour of radio sources and that the speed of expansion will be roughly constant over the range 10 < D < 500 kpc but is likely to be greater at both smaller and larger values of D.

In Fig.1 there is a dearth of sources with $P > 10^{26}$, D > 1 Mpc which would be required as the later stages of the higher P sources. Are they really there but disguised? To answer this we need to determine how fast the evolutionary tracks are traversed. The only good evidence is that of synchrotron ageing which several authors have used to deduce speeds, V, of $\sim$ c/20. If we accept the models above with V almost constant, then the cut-off frequency at a specified point between the hotspot and the nucleus, is determined uniquely by P and D provided the geometry of all sources is the same and we ignore the contribution to P from the hotspots. Thus contours of constant ν_c on the P-D diagram can be plotted for any given value of V; c/20 was chosen in Fig.1. Note the very large range in ν_c which implies that small, low P sources should show no ageing effects whereas in high P sources the effects are so large as to remove the bridge completely except at very low frequencies. This gives a good account of the structures seen in doubles at high frequencies; all double sources with $P < 1.5 \times 10^{27}$ have bridges whilst for larger P there are no continuous bridges and at very high P even the short tails to the hotspots disappear. Such objects with large values of D would be hard to pick out and may have been missed. We have one or two candidates under suspicion.

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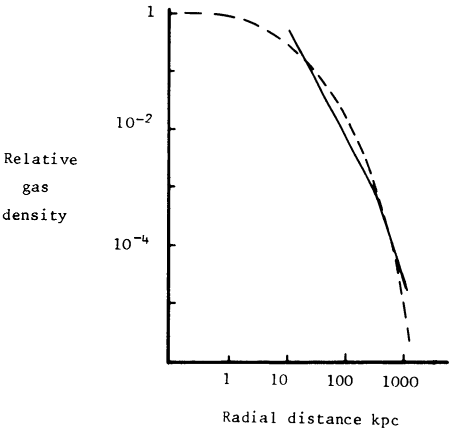

Fig 2. Relative gas density with radius in a galaxy.
Full line : Density deduced from P-D diagram and Scheuer's model.
Dashed line: Model atmosphere for galaxy with r_e = 30 kpc.

Overall, my conclusion is an optimistic one, that studies of complete samples of radio sources do provide a powerful method of investigating their evolutionary development.

REFERENCES

Jenkins, C.J., Pooley, G.G. & Riley, J.M.: 1977, Mem. R. astr. Soc., 84, pp 61-99.
Scheuer, P.A.G.: 1974, Mon. Not. R. astr. Soc., 166, pp 513-528.

DISCUSSION

LAING: Do you believe that the model of twin hot-spots moving the intergalactic medium applies to the weak sources (through jets and tails)?

BALDWIN: The right model must be different for those sources. Indeed, they grow bigger the harder one looks at them! My suspicion is that some of the jet sources could be in a steady-state and have an indefinitely large age.

SWARUP: What is the predicted effect of increasing distance on the size of radio lobes on hot spots in your model in which the density around the galaxy decreases as R^{-1} or R^{-2}?

BALDWIN: In Scheuer's original model with a uniform external medium, the bridge between the hot spots is cigar-shaped. For a density falling as R^{-2}, the bridge has a similar shape in the outer parts but is pinched to zero width near the central galaxy.

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