VII

# MORE INTERPRETATION OF COSMOLOGICAL INFORMATION ON RADIO SOURCES

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# THE PHYSICS OF RADIO SOURCES AND COSMOLOGY

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There are two important questions in which the physics of radio sources impinges upon cosmology. The first is whether the large apparent expansion velocities of certain compact sources can be explained satisfactorily within the hypothesis that their red-shifts are due to the Hubble expansion. The second is the whole broad question of the evolution of the radio source population with epoch. I do not have a new and convincing answer to the first, and the second is pretty nebulous, since we do not even understand radio sources at the present epoch very well. So I shall not present a general survey: instead, I shall use my allotted time to discuss a smaller question to which one can now give a fairly definite answer.

Malcolm Longair's first notable contribution to science was to point out that the radio source counts require not only that the source population should evolve, but that powerful sources should evolve much faster than weak sources. Ever since then he has been trying to define more quantitatively how one must fill up the P - z plane, and indeed much of this symposium has been devoted to that and closely related problems. The theoretician in each of us cannot help also wondering why. There are plenty of explanations for the greater abundance of radio sources in the past; all sorts of exciting things could have happened when the world was young and galaxies first shone forth out of the primaeval turbulence. There are fewer explanations of the fact that weaker radio sources weren't nearly as overabundant (relative to the present epoch) as powerful ones. However, there is one natural and elegant explanation, which depends on the idea that old, weak, diffuse sources are extinguished because of inverse Compton losses on the microwave background. For example, in the halo of M87 one would expect inverse Compton losses to be important over time scales $10^8$ years, and indeed this and some other weak sources (e.g. 3C 465, 3C 129) have very steep radio spectra in their outermost regions. Since the energy density of the microwave background rises as $(1+z)^4$, weak sources would have been snuffed out much younger at large red-shifts; hence the density of weak sources does not increase with z as fast as that of strong sources. This idea was worked out rather

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thoroughly by Rees and Setti (1968), and has been mentioned again in more recent papers (e.g. van der Laan and Perola 1969, Christiansen 1969, Wardle and Miley 1974). Rees and Setti took expanding spheres as models of radio sources, and computed how the luminosity function should evolve with eposh. We now have a far more profound and sophisticated ignorance of the physics of radio sources than we had in 1968, but we cannot yet make a decisive improvement on Rees and Setti's work by using better models. We also have a wealth of observations of the structures of radio sources, and can even discern some correlations between morphology and radio power P; but to check Rees and Setti's theory directly we chiefly need to know how long the fast electrons interact with the microwave background, and we do not really know the ages of radio sources to within a factor 10. Nevertheless, I think the new observational information can be used to perform a test which may be good enough to exclude the theory.

I shall make no assumption about the age of any source. I merely note that inverse Compton losses must be unimportant so long as synchrotron losses are greater, i.e. so long as the magnetic energy density is greater than two thirds of the radiation density. For the magnetic energy density I adopt the equipartition value, worked out separately for each component of a source. I then take a complete sample of radio sources (it is the subset with $S_{178} > 20$ Jy of the complete sample of 166 sources described by Longair, see final day's discussion in this volume); all the sources in this sample are either very compact or have been mapped with reasonably good angular resolution (most of them at 2" arc resolution). That complete sample provides a luminosity distribution (admittedly a rough one!) for z = 0, which is shown in the top histogram of Figure 1. (The most powerful sources in the sample are in fact at appreciable red-shifts, but, as we shall see, their distribution is not important for the present exercise since nearly all their flux density is in components of small angular size.) For each component of each source I then find the equipartition magnetic energy density, and hence the red-shirt beyond which inverse Compton loss would exceed synchrotron loss. I then make the most optimistic assumption I can about the importance of inverse Compton losses: as soon as inverse Compton loss exceeds synchrotron loss, I extinguish that component utterly. Thus I can find out how a set of sources with the same intrinsic properties would look at various red-shifts z. Some results are shown in the lower histograms of Figure 1. Some sources have vanished altogether, others have only lost some of their components. Diffuse components vanish first because they have lower equipartition magnetic fields. The resulting distributions are shown by the full lines. Some of the sources still lack red-shift measurements; if these are arbitrarily given z = 0.3 and included, the histogram rises to the upper dashed line. But what I have done so far is not quite fair; some of the sources, on losing one or more components, would have dropped below the flux limit $S_{178} = 20$ Jy of the sample. If we discard a source completely as soon as it falls below that limit (which I believe to be the correct procedure) we are left

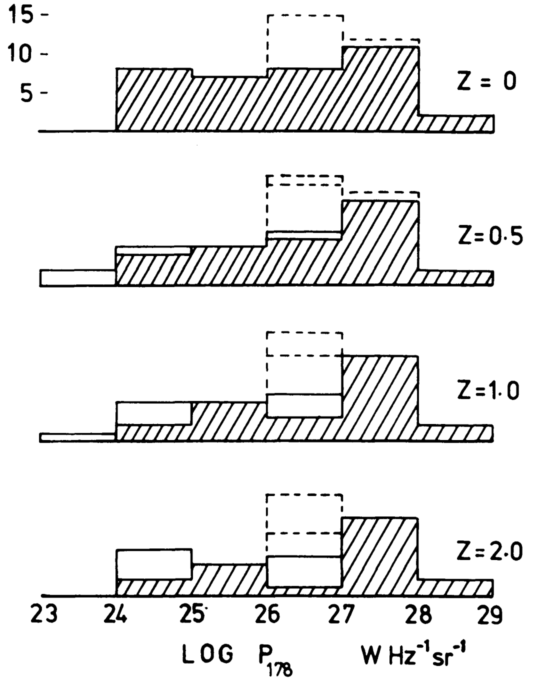


Fig. 1 Luminosity distributions at various red-shifts, derived from that at z = 0 assuming the greatest possible effects of intense Compton losses.

with the shaded histogram (or the lower dashed line, if we include sources with unknown distances as if they had z = 0.3). Now I divide each histogram by the z = 0 histogram to get the ratio by which weak sources are underevolved, obtaining Figure 2. Figure 2 again shows, qualitatively, the behaviour that we want. Now we come to the crucial comparison. Is the maximum possible effect of inverse Compton losses, shown in Figure 2, enough to account for the requirements of the source counts and red-shift distributions? The most recent estimates of the evolution of the radio luminosity function that I know are those that Wall described at this symposium, and two of his models are sketched in Figure 2. It is clear that inverse Compton scattering on the microwave background is quantitatively inadequate, by several orders of magnitude, to suppress the density evolution of weak sources to the required extent.

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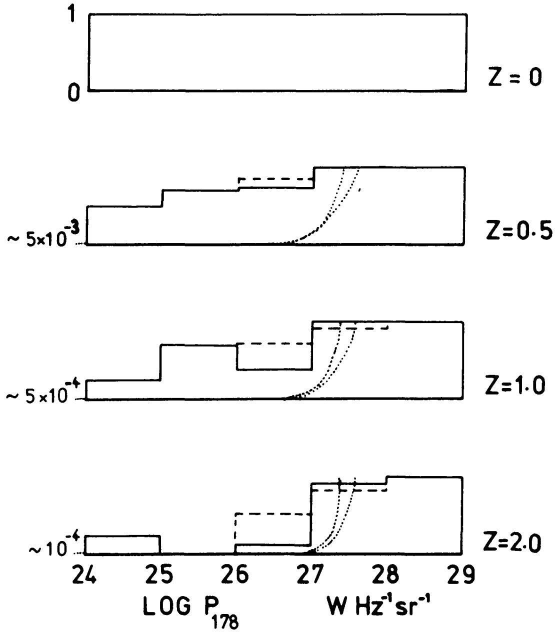


Fig. 2 The density of sources, as a fraction of what it would have been if the source density had evolved in the same way for all radio powers P. The histogram is derived from Fig. 1, i.e. assuming that variation with P is due to inverse Compton losses only. The dotted lines indicate the variation with P required according to Wall, Pearson and Longair; these curves fall to the small fractions written by the left sides of the histograms.

How reliable is this result?

(i) I have rather arbitrarily taken equipartition magnetic fields. If the magnetic energy were systematically much less than the fast particle energy, inverse Compton losses would exceed synchrotron losses (though not necessarily other e.g. adiabatic losses) at smaller z. If $B = \alpha B_{equipartition}$, we ought to use the histogram for z* at red-shift z, where $(1+z^*) = \alpha^{-\frac{1}{2}}(1+z)$. Thus we can see that the sources have to be grossly out of equipartition to make the "inverse Compton" explanation consistent with Wall's estimates of the evolution of the luminosity function. But we must bear in mind that we can't prove that the sources are anywhere near equipartition.

(ii) Some of the maps do not have enough resolution to show all of the structure. But any finer structure would represent components with larger $B_{equipartition}$, and so strengthen my conclusion.

(iii) Figure 2 does not compare theory directly with observation, but with models fitted to the observations. The weakness of evolution for weak sources is determined essentially by the convergence of the source counts at low flux densities; my impression is that this feature of the models cannot be shifted very much without contradicting the observations, but obviously it is a question that needs to be looked into.

(iv) The calculations presented here are preliminary; the statistics could be improved by using a rather larger sample.

Let me summarise the argument. Detailed mapping has shown that even fairly weak sources often have a large part of their flux density in small components. Unless these components are very far indeed from equipartition, their magnetic fields are such that synchrotron losses exceed inverse Compton losses even at red-shifts of 1 or 2. When one looks at the argument in this way, I think it becomes clear that the conclusion is not likely to be changed by minor tinkering with the radio source parameters.

I conclude, rather reluctantly, that we have to look for something intrinsic to the sources to account for the weaker evolution of weak sources.

I am indebted to Ann Simon for permission to use her computations of magnetic field strengths in radio sources, without which this talk would certainly not have been ready in time for the symposium, and to Drs. Wall, Pearson and Longair for permission to use their estimates of the evolution of the radio luminosity function before publication.

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DISCUSSION

*Conway:* Is it possible to turn your argument right round and argue that since the Inverse Compton effect has not completely wiped out every radio source, B must be within some factor of the equipartition value. If so would that set an upper or lower limit to $B/B_{equipartition}$?

*Scheuer:* No, I can't turn the argument around, because I am using an inequality. Something other than synchrotron losses could (and in most cases probably does) extinguish sources before inverse Compton losses affect them.

*Trimble:* How far out of equipartition do the sources have to be to make inverse Compton losses important enough to account for the required evolution?

*Scheuer:* Looking at Figure 2, one sees that inverse Compton losses at z = 2 are still insufficient to fit the luminosity function for z = 0.5. Thus one has to decrease the field by a factor exceeding $(2/0.5)^2 = 16$ below equipartition before inverse Compton losses become sufficiently effective. With a more detailed analysis I think one could sharpen that statement quite significantly.

*Rowan-Robinson:* Some time ago (MN, 150, 389, 1970) I tried to fit models of this type to the radio source-counts, with density evolution combined with this inverse Compton snuffing-out to give a luminosity-dependent cut off. I would agree that equipartition doesn't work, but a model in which the electron energy is the same in all sources, with the magnetic field varying, can fit everything. You have to be careful not to exceed the integrated X-ray background with the inverse Compton radiation.

*Scheuer:* Thank you for reminding us of this work. In the calculations described here, my purpose was to use observations rather than models; this has only become practicable fairly recently, thanks to the availability of more detailed radio maps and more measured redshifts.

*van der Laan:* It seems to me that spectral index distributions demonstrate that the sources are snuffed out, not by radiative losses, but by processes that uniformly suppress the emission throughout the radio window. The fact that for much deeper samples $g(\alpha)$ does not show any flux dependence, reinforces this conclusion. (See P. Katgert, this volume).

*Scheuer:* I have used synchrotron losses only as a lower bound to other losses, a lower bound that is easy to compare with inverse Compton losses. Personally, I should agree with you that sources probably fade chiefly because of processes, such as adiabatic loss and field line reconnection, which do not change the radio spectrum (cf. Jenkins, C.J. & Scheuer, P.A.G., 1975, M.N., 174, 327), though I doubt whether this is generally accepted. However, there are no firm estimates of the rates of such processes in radio sources, so I can't use them here.

*Schmidt:* Optically selected quasars show a cosmological evolution similar to that of strong radio galaxies, suggesting a common explanation. Since inverse Compton losses are unlikely to affect the very compact optical quasars, it is perhaps agreeable to see them ruled out, too, as a cause of radio galaxy evolution.

*Okoye:* Is it not true to say that not knowing the actual values of the magnetic field strength in the source components, it is not then reasonable to assume that inverse Compton losses are less than intrinsic synchrotron losses (or if inverse Compton losses are greater, then some disappear) while at the same time assuming that the source magnetic field strength is the equipartition value.

*Scheuer:* Yes, I agree. I am sorry if I did not make that sufficiently clear. You can keep inverse Compton losses as the cause of differential evolution between strong and weak sources, if you assign magnetic fields far below equipartition values to the compact parts of weak radio sources. That does not appeal to me, because the more compact components seem to have quite normal radio spectra, but you are quite right to point out that my calculations do not rule out the possibility.

## THE ORIGIN OF THE EXTRAGALACTIC RADIO BACKGROUND AT LOW FREQUENCIES

Ann J.B. Simon

At low frequencies the isotropic extragalactic component of the radio background peaks at about 3 MHz and then decreases. Independent evidence that the component from outside the Galaxy peaks at about this frequency is provided by A.H. Bridle (1968, Nature, 219, 1136) in his interpretation of the lack of an absorption feature in the direction of the Magellanic Clouds in observations by G. Reber (1968, J. Franklin Inst., 285, 1) at 2.1 MHz. The brightness temperature at 178 MHz is 23 ± 7 K for $\alpha = 0.80$ and can largely be attributed to the sum of contributions from extragalactic radio sources. I shall outline an attempt to explain the turnover at 2 MHz in terms of absorption in the individual sources which make up the background.

A complete sample of radio sources (See Appendix) is taken and a model built for each source. The only absorption effect found to be significant was synchrotron self-absorption. The frequency at which the luminosity of a source is a maximum (the synchrotron self-absorption frequency) is found to be directly related to the source luminosity, ranging from 1 MHz for low luminosity sources to over 100 MHz for high luminosity sources. The integrated background radiation was computed for $\Omega = 1$ for an evolving Universe of the type described by Wall (this volume) and a non-evolving Universe for comparison. Both spectra peaked at about 1 - 2 MHz and obeyed the power law $B(\nu) \propto \nu^{-0.8}$ at 178 MHz. The evolving model predicted $T_b = 15$ K at 178 MHz. Calculations of the background radiation from sources in different luminosity ranges showed that for a non-evolving universe the peaks of each contribution ranged from 1 MHz ($P_{408} \leqslant 10^{24}$ W Hz$^{-1}$sr$^{-1}$) to 15 MHz ($P_{408} \geqslant 10^{28}$ W Hz$^{-1}$sr$^{-1}$). The background for an evolving universe is therefore bound to turn over somewhere in this frequency range, whatever model of evolution is used. Even for the evolving Universe, the non-evolving low brightness sources contribute a very large fraction of the background at all the frequencies considered.

Investigation of the spatial origin of the background radiation showed that at least half of the background at all frequencies in the range 0.5 - 178 MHz originates at redshifts less than 1.0, and that the contributions become progressively smaller for regions of higher redshift. This minimises the effects of possible absorption by either intergalactic gas or normal galaxies. It can therefore be concluded that the superposition of individual sources leads to a turnover in the radio background at about 2 MHz due to synchrotron self-absorption in the sources. A large fraction of the background comes from low-luminosity sources. The contribution to the background from sources at redshifts greater than about 2.0 is very small.

*Feldman:* What percentage of the extragalactic background at about 1 MHz is due to clusters of galaxies?

*Simon:* I don't think this can be meaningfully evaluated since the number of sources associated with Abell clusters in the sample I have used is very small.

*Jaffe:* I wouldn't take the absence of thermal absorption in the direction of the Magellanic Clouds as typical of the Galaxy as a whole since the gas in the Galaxy is very patchy, and the area of the Magellanic Clouds is known to be an area of low optical absorption, indicating a low gas content in that direction.

*Simon:* I would agree that it cannot be taken as a hard fact but it does suggest that the extragalactic component has decreased by 2.1 MHz. It is impossible to make any more definite deduction from the data available.

*Conway:* I believe your graphs refer to a universe with $\Omega = 1$. Have you evaluated the case with low $\Omega$? I would expect that the chief difference would be to make the most important z-range further away.

*Simon:* No evolving model is yet available for low $\Omega$. If the computation is done for a non-evolving $\Omega = 0$ model, the contribution from the range $0.0 \leqslant z \leqslant 1.0$ still dominates.

*Gulkis:* Can you please explain how the R.A.E. satellite data are separated into a galactic and radio source component, and in particular how you know that the radio source spectrum turns over abruptly in the 1 - 10 MHz spectral region?

*Simon:* The original paper (Clark, Brown and Alexander, 1970, Nature, 228, 847) explains how the spectrum was broken down into two components by the best fit method, which showed that the extragalactic component arriving here has a sharp turnover at about 3 MHz. This could be due either to absorption of a power law by thermal electrons equivalent to a free-free optical depth of at least 3 at 1 MHz, or to a turnover in the true extragalactic spectrum with smaller optical depth inside the Galaxy. In view of the probable patchiness of the electrons inside the Galaxy, I think the latter interpretation is more likely.

## THE DISTRIBUTION OF INTRINSIC SEPARATIONS OF 3CR DOUBLE RADIO SOURCES FOR RADIO GALAXIES

K.C. Jacobs

For the 3CR radio galaxies with measured redshifts the observed angular separation between the components of each radio source may be converted into an apparent separation, d (kpc) [$H_o$ = 50 km $s^{-1}Mpc^{-1}$]. The usual histogram of number of cases with d in logarithmic (decade) bins is sharply peaked at several hundred kpc. However, this "log-binned-log-histogram" is misleading, since it is a severely distorted representation of the quantity of physical interest, namely the probability density function, f(d). We invert the histogram to obtain the observed f(d), which decreases monotonically with increasing d. Since uniform-spherical angular projection effects transform the intrinsic probability density, F(d), into the apparent f(d) via

$$f(d) = d \int_d^\infty \frac{F(D)\ dD}{D\sqrt{D^2-d^2}}$$

we may deduce F(D). The distribution of intrinsic separations, D, is essentially a decaying exponential function with an e-folding parameter, $D_o \approx 300$ kpc.

Three interpretations of the resulting F(D) are given:

(i) If the double components are separating with uniform speed, $v_o$, then the source lifetimes must be roughly exponentially distributed with the characteristic lifetime, $t_o \approx D_o/v_o$.

(ii) If the components are decelerated as they separate then the lifetimes are distributed even more steeply than exponential,

(iii) Finally, and most interestingly, if the lifetimes of all sources are approximately equal (and our observations have sampled them fairly uniformly), then F(D) implies that the components of the radio doubles are accelerating apart! Should this interpretation be the correct one, then the only extant theory of double radio sources which can survive is some version of the so-called "beam models".

## TWO TESTS OF THE EXPANSION OF THE UNIVERSE

W.H. McCrea

Discussion at the symposium indicates that the following tests may be on the verge of feasibility:

<u>Peculiar motion</u> In a region of the Universe at distance giving redshift z, let $\bar{v}$ be the mean speed of peculiar motion of gravitationally independent systems (field galaxies, clusters). Then expansion requires

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$$\bar{v} \propto 1 + z$$

(at any rate, roughly). A speaker quoted 200 km/s as a possible estimate of v in our cosmic vicinity; this would imply $\bar{v} \approx 400$ km/s at z = 1 and so on. The test is to look for any effect that depends upon peculiar motion and to see how it varies with z, or any parameter depending on z.

Hubble motion For a region of the Universe at redshift z, let θ be the observed angular size of objects of some standard class, and let φ be the observed angular distance to some object of some standard class that is gravitationally independent of the first object. Then, for some reasonable definition of the means < >

$$\frac{\langle\phi\rangle}{\langle\theta\rangle} \propto R(t) \propto \frac{1}{(1+z)}$$

The test is to get statistics of θ, φ, z. By using 3 parameters in this case we get, in principle, a test of the expansion in any region that is model-independent.

Conversely, the relation might be used as a test to see whether objects of certain classes are at the same distance - a test that would be independent of redshift.

*Wittels:* For the Hubble-velocity test of R(t) dependence on z, does one need to pair sources at the same z.

*McCrea:* Yes, but with sufficient ingenuity I think you could invent a statistical way of doing it without that restriction.