Chapter 20

THE COUNTING OF RADIO SOURCES: A PERSONAL PERSPECTIVE

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Abstract

This article gives the author's personal perspective on the continuing efforts by radio astronomers to determine the nature of the cosmological model by counting radio sources in the universe out to different levels of faintness. Although initially the source counts were expected to reveal the underlying geometry of space and time, subsequent experience showed that the issue is mixed up with the physical properties of the sources and their evolution with epoch. It is shown, how the earlier claims of disproof of the steady state model through source sounts, turned out to rest on very uncertain evidence.

1. INTRODUCTION

When Naresh Dadhich asked me to write an article for this volume, I was hesitant, as I was not aware that festchrifts as a rule permit self-action. However, he then produced a few examples, where this had happened, and I therefore agreed to contribute an article. It describes an area of astronomy to which I was drawn willy-nilly from my early research student days, and to which I have returned from time to time. I refer to the counting of radio sources in order to test the validity of a cosmological model. From a perspective four decades later, the issues involved look different from what they seemed in the late fifties and the early sixties.

This is therefore a historical account, and a highly personal one, and consequently open to the charge of being biased. But in this somewhat

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contoversial field, it will be very difficult to find an account that is completely neutral!

So let me begin with the basic cosmological test itself, as ideally conceived, and then come to the trials and tribulations of translating it into reality.

Suppose we live in a uniform Euclidean universe which has a uniformly distributed class of sources of radiation, each with a luminosity L. Let n denote the number density of such sources in the universe. We therefore expect the number of sources within a distance R from us, to be

$$N = \frac{4\pi}{3} n R^3, \tag{1}$$

and the faintest of these will be those on the periphery of the sphere of radius R centred on us. The flux received from each of these sources will be

$$F = \frac{L}{4\pi R^2}. \tag{2}$$

In general if we count the number N of sources brighter than F for a range of values of F, we will get a plot of points in the log N-log F plane, lying on a straight line given by

$$\log N = -1.5 \log F + \text{constant}. \tag{3}$$

In other words, we expect the slope of the log N-log F line to be -1.5. In our later discussion of radio source count we shall have frequent occasions to describe the slope of the source count curve in the above sense. We will refer to the 'slope' by magnitude: thus in the above example, the slope is 1.5. Likewise, a slope of 1.8 is steeper than a slope of 1.5, although in source count equations like (3) above, the slopes are negative.

In optical astronomy, we may wish to count galaxies, in which case the appropriate quantity for F will be the apparent magnitude m. Since

$$m = -2.5 \log F + \text{constant}, \tag{4}$$

the above relation becomes modified to

$$\log N = 0.6\, m + \text{constant}. \tag{5}$$

In other words, the curve of log N plotted against m should be a straight line with a slope of 0.6. Likewise, if we are counting radio sources, then the relevant measure of flux received is the flux density S, which measures the flux received in a relatively narrow bandwidth, usually 1 Hz. In this article we are mainly concerned with the counts of radio sources and hence will be discussing the log N-log S relation.

If we wish to extend this result to *non*-Euclidean cosmological models, such as those used for describing the expanding universe of modern cosmology, naturally the prediction will be different. We keep all other assumptions the same but change the Euclidean spacetime to the Robertson-Walker spacetime given by the line element

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right], \tag{6}$$

where we have used the standard notation for the coordinates, and $a(t)$ denotes the expansion factor. The space-curvature is denoted by the parameter k which can take values, $0, 1, -1$. The coordinates r, θ, ϕ are the constant comoving coordinates of a typical galaxy and t denotes the cosmic time.

The relations derived above for the Euclidean geometry can be obtained for the above models also. In the standard Friedmann cosmology, the simplest generalization is that the number density of sources in the comoving coordinates is constant with respect to t. For details see some standard text in cosmology (e.g. Weinberg 1972, Narlikar 1993). The question is, can the actual number count tell us whether any of the wide ranging cosmological models described by the RW-line element above comes closest to reality?

This is the basic issue to be discussed here.

2. HISTORICAL BACKGROUND

One of the first attempts to try this test with galaxies as the sources to be counted, was made in the 1930s by Edwin Hubble, who hoped to measure the curvature of space (the parameter k) through this observation. However, for the data to be decisive enough, one needs to go to high redshifts, and hence counts of a large number of galaxies is involved. Moreover, the other assumption in the test is that all sources are equally powerful, which also is not the case in reality. The sheer enormity of the operation rendered the test impractical and Hubble eventually abandoned it. However, one salutary effect this abortive operation had on observational astronomy was that the proposed test provided motivation for building a large telescope, and that is how the 5-metre telscope got built on the Palomar Mountain!

The radio astronomers got into this game in the mid-fifties, when they realized that a substantial part of the radio source population is extragalactic, and that their number density is considerably lower than that of galaxies. Thus by counting relatively fewer number of sources, there was the chance of obtaining the answer Hubble was looking for.

Hubble's procedure was to compare the predicted galaxy count with the observed one. Instead of the number-magnitude relation, the radio astronomers had a number-flux density relation for radio galaxies. What does a typical relation look like?

The qualitative signature of a typical expanding universe model is to flatten the log N-log S curve as one goes from high to low flux levels, that is to progressively reduce the slope from 1.5 to lower values, 1.4,1.3,1.2,..., because of the redshift effect on flux densities and volumes. Thus, it was claimed that the test was a powerful tool for distinguishing between cosmological models.

Martin Ryle (1955) from the Mullard Radio Astronomy Observatory of the Cavandish Laboratory in Cambridge announced the first result based on his early catalogue of radio sources in the Halley Lecture delivered on May 6, 1955, where he got a slope of the log N-log S curve to be 3.0. Thus, with a magnitude exceeding 1.5, the curve was *steeper*, instead of flatter than the Euclidean value.

Prima facie, the result seemed to disprove all expanding universe (big bang) models. However, there is a loophole in such models. Because the universe is evolving, one could argue that the number density of radio sources in the past was greater than at present. By suitably adjusting the number density n as a function of the cosmic time t, *any* slope can be accommodated. The alternative also exists that the luminosity L is a function of t, and between the two variations the fit to the observed data could be achieved.

There is one model, however, which does not have this freedom of choice. This is the steady state model, wherein the universe has the same physical properties at all epochs. Thus the n and L values for any source population cannot be epoch dependent. For such a model, prima facie, a slope as steep as 3 spelt doom. Indeed, Ryle, who never liked the steady state theory, took pains to underscore this conclusion.

There was, however, the alternative possibility that the counts could have been in error. Indeed, in 1958, Ryle and his colleagues (Archer, et al 1959) revised the index down from 3 to 2.2. Although the credibility of the claim suffered somewhat by this drastic come-down, the revised finding was again projected with great certainty as clearly disproving the steady state theory.

In the meantime, the Australian radio astronomers had been conducting their own surveys largely of the southern sky, although having an overlap region with Ryle's northern sky. Mills and Slee (1957) announced that their results showed a slope not significantly different from the Euclidean slope of 1.5. Based on their study of the overlap region, they pointed out possible sources of errors, which might have affected

the data reduction by the Cambridge group leading to their claimed steeper slope.

These results related to the 3C (Third Cambridge) Survey. In 1960, Ryle announced a new result related to the 4C Survey which had fainter (and hence assumed to be more distant) sources. The slope this time was claimed to be 1.8, and because the new survey had more sources, it was claimed to be more accurate. Surely, argued Ryle, this finding disproved the steady state theory conclusively.

This is where I was drawn into the controversy.

3. A DEFENCE OF THE STEADY STATE THEORY

In June 1960, when I approached Fred Hoyle with the request to be my Ph.D. guide, he readily agreed and suggested a number of interesting lines of investigation in astronomy and astrophysics. However, when discussing cosmology, he did not mention the steady state theory, which I had found an attractive approach to the study of the universe. He said that although there were many challenging problems in that theory, he wished to keep a research student away from controversy. Consequently, I set to work on an idea proposed by Heckmann and Schucking on spinning universes. The problem was to see if spin allows non-singular cosmological models, models which oscillate with finite upper and lower scales of size. I was then to look at the problem of primordial nucleosynthesis in such models.

Within six months, however, I had reached a dead end, i.e., I could see that the Heckmann-Schucking models would not lead to non-singular oscillating models as their authors had claimed. So the next part of my investigation did not arise. I thus found myself somwhat at a loose end in January, 1961. This was when the Hoyle-Ryle controversy broke out.

For, of the three originators of the steady state theory, Hermann Bondi and Tommy Gold did not take Ryle all that seriously, dismissing the claim as just one along the line of earlier claims in which the announced slope had steadily come down from 3 to 2.2 to 1.8. Perhaps further errors may be discovered in the future which would lower the slope further to the Euclidean 1.5, which the Australians were happy with, anyway. It was only Hoyle who took the results seriously enough to realize that a threat to the steady state theory indeed existed.

The Hoyle-Ryle confrontation took place at a press conference given by the latter. As recalled by the former in a recent book (Hoyle, et al 1999), it did not help in making their personal interaction any easier. Ryle, however, realized that for a peer-understanding of his findings, he had to present his work not before the media but to a body of scientists. Accordingly, he arranged to describe his results during the February 10 meeting of the Royal Astronomical Society. It was expected, that Hoyle would reply to his claimed disproof of the steady state theory. Indeed there was great expectation of a lively scientific confrontation in a society which had previously witnessed controversies between Milne and Eddington, Eddington and Chandrasekhar, etc.

Hoyle, as mentioned earlier, had not been dismissive of Ryle's data; rather his attitude had been that given the observational uncertainties, it was still possible to fit a realistic steady state model to the observed source counts. This was when he asked me to work out on an idea that might possibly serve the purpose. To begin with we needed to get the data from Professor Ryle and his colleagues. This was, however, not so easy, as the Cavendish group was very secretive about its findings. Rather than get a catalogue of sources with flux densities from which one could prepare tables and plot curves, all we got from Ryle after a tea-time discussion was a hand-drawn log N-log S curve, with a few points marked for numbers and flux densities. The curve had a slope of 1.8 which Ryle challenged us to reproduce within the cosmological framework of the steady state model.

However, it was already mid-January and in order to have a viable model ready for reporting we had to work 'overtime' during those three weeks or so. I shall come to the model and its aftermath in the following section. Here I recall using the EDSAC computer with punched paper tape and machine language programming as well as hand operated Facit calculators to churn out the numbers. The numbers came out fine: the theory could indeed reproduce Ryle's steep slope within the framework of the steady state theory. We thus had a counter-example to Ryle's claim. We then had to persuade the Engineering Labs to make at short notice a few 'lantern slides' based on our calculations. We managed to get everything organized with a couple of days to spare.

However, in the meantime, Fred Hoyle had set off a bomb-shell so far as I was concerned. He had discovered that he had a prior engagement to speak at a college in London on February 10, and so he would not be able to attend the RAS meeting at all. Instead, *he asked me to reply to Ryle!*

So here was I, a raw research student with barely six months of research experience now launched into the limelight of a major controversy. However, Hoyle assured me that with the mathematical backing we had for our model, I should be able to handle any counterattack. He drilled me, nevertheless, in speaking concisely so that I could convey the salient

features of our model within ten minutes. He made sure that the RAS would allot me that much time for presenting our counter-example.

In the end, my presentation went well. Ryle raised a minor protest that this seemed a new version of the steady state theory. However, Bondi who was quick to see the point behind our approach rose to its defence. In any case I came back from the meeting considerably elated and with a newly acquired confidence that I had now been groomed into participating in scientific debates. This experience has stood me in good stead in facing other astronomical controversies.

4. RADIO SOURCE COUNT IN THE STEADY STATE COSMOLOGY

Let me recall the model we had proposed early in 1961. It rested on two premises:

1. The universe is inhomogeneous on the scale of 50-100 Mpc, being made of superclusters and voids.

2. The probability of a galaxy becoming a radio source increases with its age τ, being proportional to $\exp[4H\tau]$.

The rationale behind these two assumptions as perceived then was as follows. The 'hot universe' model of the steady state universe proposed by Gold and Hoyle (1959) envisaged that galaxies would form typically in large groups with characteristic dimensions of 50-100 Mpc. Thus the theory envisaged an inhomogeneity on this scale. In the late 1950s and the early 1960s only one observational astronomer G. deVaucouleurs was talking of the 'Local Supercluster', and he was generally not taken seriously by the majority which believed in universal homogeneity beyond the cluster scale. There was, however, evidence already for 'second order clustering' from the work of George Abell (1958), who had done an extensive analysis of distribution of clusters on the sky. Thus there was both theoretical and observational support for the first assumption.

The second assumption was based on the finding then emerging, that the property of radio emission seemed confined largely to elliptical galaxies, which are generally considered old. Thus the correlation of radio property with age was conjectured through the second assumption. At the time, the radio astronomers tended to believe that radio emission arose from collisions of galaxies. Which is why, there was a ready acceptance of the Cambridge belief that the number density of radio sources was significantly higher in the past: in a big bang universe, the density of galaxies was higher in the past and hence the chances of collisions were greater. The collision hypothesis had already been demonstrated as theoretically untenable by the work of Geoffrey Burbidge, whose estimates of the energy of a typical radio source emitting synchrotron radiation, were far higher than the energy of collision of two galaxies (Burbidge 1959). Subsequently, in a few years, the collision idea received a decent burial; however, belief in the notion that the process of radio emission had to be more frequent in the past persisted.

In the steady state theory, however, no appeal could be made to an epoch-dependent process, as the word 'steady' forced one to regard the average state of the universe to be the same at all epochs. The second assumption, however, coupled with the first one, led to an apparently evolutionary effect *in a local statistical sense*, as follows.

In the steady state theory, the age-distribution of galaxies follows the formula:

$$Q(\tau)d\tau = \exp(-3H\tau)d\tau, \tag{7}$$

where $Q(\tau)d\tau$ denotes the number density of galaxies in the age range $[\tau, \tau + d\tau]$. Thus to observe very old galaxies, a typical observer would have to sample a larger volume, and hence look out to farther distances. Hence, one expected that a generic observer would begin to see an increasing density of radio sources (which by assumption 2 were more likely to be found in older galaxies) at larger distances. This effect was in a sense a statistical fluctuation from the 'average' situation which was represented by the completely homogeneous Robertson Walker line element for the steady state theory, with $a(t) = \exp Ht$. In other words, after a somewhat local steepness, the log N-log S curve would revert to the standard progressively flattening form described earlier.

In 1961 we published a detailed version of this model (Hoyle and Narlikar 1961), followed by another carrying out computer simulations of the real universe, in the following year (Hoyle and Narlikar 1962). In retrospect, I think these papers were pathbreaking on the following counts, although because of the general feeling of hostility against the steady state theory these aspects went unnoticed at the time.

1. They introduced the idea of a universe inhomogeneous on the scale of superclusters and voids with typical length scales 50-100 Mpc, an idea that became accepted as reality two decades later, although at the time it was seen as introducing unnecessary complications into cosmology.

2. The idea of counting a source population which was evolving with age became standard practice in the big bang cosmology, from mid-sixties onwards, although it was first introduced here in the framework of the steady state theory.

3. The second of these papers used Monte Carlo techniques to simulate source distributions on a computer, and these were counted by random observers to demonstrate fluctuating source counts at high flux levels. I believe, this was the first simulation of its kind in cosmology, and was made possible because Fred Hoyle had rented time on the IBM 7090 machine in London. In today's desktop workstation environment it is difficult to imagine the mode in which we were operating, viz. going to London once a week with our punched cards which were to be handed over to the computer staff in the morning and the results collected in the evening. If the programme had a serious bug, one had to wait for a week to sort it out!

4. Although a super-Euclidean slope was seen as a clear indication of support for big bang, it could clearly not be sustained at low flux densities. Our model naturally led to a flatter curve at low flux densities, which was borne out by later surveys.

5. We had estimated the majority of sources to be of medium power at modest redshifts, whereas Ryle and his colleagues believed them to be typically very powerful and very distant. The issue could not be settled till the sources could be optically identified and their redshifts measured. This is a slow process, and to date only the 3C Revised catalogue has all sources optically identified and their redshifts measured. As we shall see later on this account, the data have turned out to be closer to our interpretation rather than to that of the Cambridge radio astronomers.

5. QUASARS VS RADIO GALAXIES

While we were working on this paper, Fred Hoyle arranged to visit Hanbury Brown at the other premier radio observatory in Britain, the Nuffield Observatory at Jodrell Bank. Hanbury Brown had just carried out a study of radio sources, especially their angular sizes. He had noticed that there were quite a few which were too compact for their angular size to be measured by interferometric techniques. What were these 'chaps', as he called them? In any case their presence indicated that the population of radio sources was by no means homogeneous, and hence basing cosmological deductions on them might be misleading. [As a sound precaution, it is best to understand the class of objects you are counting, before drawing profound conclusions from them.]

To study these compact sources, it was essential to optically identify them, measure their redshifts and other physical features. The positions given by radio astronomers needed to be made more precise for optical identification to be attempted.

During 1962, the special technique of lunar occultation used in Australia enabled the position of the compact source 3C 273 to be measured accurately. In 1963, the source was optically identified and its spectrum examined. The resulting finding of a redshift of ~ 0.16, despite the extraordinary optical brightness (13^m) of the source, suggested that here we are looking at a new class of radio sources. Later months brought to light several of these objects which, because of their starlike appearance, eventually came to be called *Quasi-Stellar Objects*, (QSOs) or *quasars*. Clearly the radio astronomers were looking at mixed populations of radio galaxies and quasars. It made more sense to separate the two before counting them in order to draw cosmological conclusions.

Using the maximum likelihood method of determining the slope of the log N-log S curve, Jauncey (1967) pointed out that the 3CR catalogue had three kinds of sources, (i) radio galaxies, (ii) quasars and (iii) unidentified sources. Of these, the radio galaxies had a slope not significantly different from the Euclidean 1.5, while the quasars showed a steeper slope ~ 2. So far as quasars are concerned, there are reasons, not widely accepted but still not completely disproved either, castinging doubts on the cosmological interpretation of their redshifts.

In his lecture at the Royal Society, Fred Hoyle (1968) discussed the source counts as he perceived them at the time. The steepness of the source count curve for the three types of sources turned out to be not significantly different from 1.5 for (i) radio galaxies and (ii) quasars, but was 2.5 for (iii) the unidentified sources. For radio galaxies, which do not have very large redshifts, the slope 1.5 is not cosmologically significant; nor is it so for quasars if their redshifts are not cosmological. *The slope is, however, cosmologically significant and inconsistent with the steady state value for the quasars if their redshifts do follow Hubble's law.* What about the sources of class (iii)?

The number of unidentified sources was however, small and the implication of their steep slope was like this, as pointed out by Hoyle. There are 10 unidentified sources at $S = 12.5$ Jy and 93 at $S = 5$Jy, which gives the 2.5 slope. However, suppose that we don't know the value of N at the high flux level and wish to determine it on the assumption that the slope is 1.5. Thus the number at the high flux level $S = 12.5$ Jy is 23. Had there been 23 instead of 10 sources at the high flux end, the observed slope would have been 1.5. The observed deficit is thus of 13 sources over 3 steradians, i.e., about 4-5 sources per steradians. The Hoyle-Narlikar model of radio source evolution described above, allowed for this deficit by the probability law proportional to $\exp[4H\tau]$. In short, we are in a local hole which has a deficit of radio source activity. Since our model did allow for local inhomogeneity (–which is now being observed), such a local hole was not inconceivable.

As pointed out by Hoyle, Ryle's interpretation of the above data would be different, however. Suppose we have a 1.5 law with the high flux value given, i.e., $N = 10$ at $S = 12.5$Jy. What is the expected number at $S = 5$? The answer is 40. Thus the observed number 93 represents an excess of 53 sources, i.e., about 18 sources per steradian. A strong evolution is required to explain this rise, as per the big bang cosmology, an evolution that cannot be accommodated within the steady state theory.

The issue thus became one of local fluctuations (limited to say 50-100 Mpc) if Hoyle's interpretation is accepted versus a cosmologically significant evolution, if Ryle's view were adopted.

6. IS EVOLUTION NECESSARY?

The case of the 3CR survey was finally resolved when almost all of its sources were optically identified and had measured redshifts, thanks to the efforts of Spinrad, et al (1985). In 1985, of the 298 sources of the Spinrad compilation of redshifts in the 3CR catalogue, 195 were radio galaxies, 53 were QSOs and 38 were unidentified. If one avoided the low galactic latitude sources with $\|b\| > 7\,\mathrm{deg}$, $S \geq 10$Jy, there were 163 radio galaxies. DasGupta, et al (1988) studied this sample to see if there were any need to postulate evolution over and above the standard Friedmann evolution of spacetime geometry. The procedure adopted was simple and straightforward. First, we take a generic Friedmann model which is characterized by the deceleration parameter q_0. Writing the bolometric luminosity distance in this model as $D = (c/H_0)x$, (H_0=Hubble's constant) we have the well known relation

$$x = \frac{1}{q_0^2}[q_0 z + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1] \qquad (8)$$

between the luminosity distance and redshift. This relation can be inverted to give

$$z = q_0 x - (q_0 - 1)[\sqrt{1 + 2x} - 1]. \qquad (9)$$

Note that, the above relation is valid also for radio sources with spectral index 1.

Next we see how the radio luminosity function $g(L)$ is completely determined if we assume no physical evolution. We define the number of sources per unit proper volume brighter than a given luminosity L as

$$F(L) = \int_L^\infty g(l)dl, \quad (10)$$

with the expectation that $F(L) \to 0$ as $L \to \infty$. If the survey is limited to flux densities $S \geq S_0$, say, then the sources of luminosity L will appear in the survey, provided

$$L > 4\pi(c/H_0)^2 S_0 x^2. \quad (11)$$

A little manipulation with the Friedmann geometry then gives the number of sources with redshifts in the range $z, z+dz$ as

$$dN = \left(\frac{c}{H_0}\right)^3 \Omega \frac{x^2}{(1+z)^3\sqrt{1+2q_0 z}} \times F\left[4\pi\left(\frac{c}{H_0}\right)^2 S_0 x^2\right] dz. \quad (12)$$

Writing $G(z) = dN/dz$, which can be determined by observations, we can invert the above relation to write:

$$F(L) = \left(\frac{H_0}{c}\right)^3 \frac{G(z)(1+z)^3\sqrt{1+2q_0 z}}{\Omega x^2}, \quad (13)$$

where x is determined from:

$$x^2 = \frac{L}{4\pi(c/H_0)^2 S_0}, \quad (14)$$

and z is given by the equation (9) in terms of x.

Thus, the important conclusion is that *the radio luminosity function is completely determined by the observed* $G(z)$. The RLF can therefore be used to compute the number of sources expected in a typical small cell $z_1 \leq z \leq z_2, S_1 \leq S \leq S_2$ in the (z, S) plane. These predicted numbers can be compared with the observed ones through the χ^2–test. Dasgupta et al (1988) carried out the test and found that the fit is statistically good. At a more sophisticated level, they also applied the Kolmogorov-Smirnov test adapted to two-dimensional distributions along the lines discussed by Peacock (1985). Again, the fit is good, without having to introduce any evolution of luminosity and/or number density of sources.

However, DasGupta (1988), also found that a similar analysis applied to the steady state theory produces not only a good fit, but a *better fit* than for the Friedmann cosmologies. Both the χ^2– and the Kolmogorov-Smirnov tests turn up better figures for the steady state theory than for the non-evolving standard Friedmann models.

7. CONCLUSION

Thus I believe, so far as the 3CR catalogue of radio sources is concerned, the Hoyle-Ryle controversy has been laid to rest. The technique followed in the previous section can be used only for the complete flux-limited samples which have all redshifts known. So far no other such samples are available. The log N - log S curve does not contain information on redshifts and is thus likely to be less definitive.

In any case, the standard big bang approach involving fitting the observed curve to the theoretical one which folds in evolutionary parameters, defeats the original purpose of Hubble, that of determining the geometry of the universe by counting sources.

Acknowledgments

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