THE NATURE OF THE RADIO SOURCES

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Optical search in the positions of radio sources has led to the certain identification of some eight sources with galactic nebulosities, and nineteen with extragalactic nebulae.

Three of the galactic nebulosities represent the remains of supernovae observed optically, and three others are probably caused by earlier supernova outbursts; other radio sources at low galactic latitudes may therefore arise from similar outbursts which occurred before recorded history.

Of the extragalactic sources, apart from the Magellanic Clouds and another small irregular galaxy NGC 55, eight sources represent the emission from nearby galaxies having a total radio emission comparable with that from the Galaxy. The remainder are sources of very much greater radio "luminosity" and five of them represent collisions between pairs of galaxies.

It is not possible to establish from such a small sample the nature of the majority of the radio sources, although since most of the sources away from the plane have been found to have small angular diameters, they cannot be explained in terms of "normal" galaxies, nor, because of their angular distribution, in terms of supernova remnants.

We have, therefore, made an analysis [1] of the available radio evidence to determine the category in which most of the sources should be placed. Initially, for simplicity it will be assumed that most of the sources belong to a single class having the same radio emission P per unit solid angle, and average space density ρ. In the detailed analysis it is necessary to examine the possibility that comparable numbers of galactic and extragalactic objects might contribute to the sources observed in a given range of flux density; it is also important to investigate the effect of a spread in the radio luminosity P within a single class.

In the present contribution the method will be given in outline only, and some of the results presented.

The number of sources per unit solid angle that will be observed with a flux density greater than S is: $N = \frac{1}{3}(\rho P^{3/2})S^{-3/2}$, and the constant $\rho P^{3/2}$ may be established from the observed counts of sources falling in different ranges of flux density. The possible values of P and ρ may be represented on a graph of $\log P$ against $\log \rho$, where they must lie on a straight line of slope $-3/2$. The position of the line is determined by the numerical value of $\rho P^{3/2}$ determined from the observations.

We can then apply further restrictions from the observed isotropy of the sources, and from their contribution to the general radiation.

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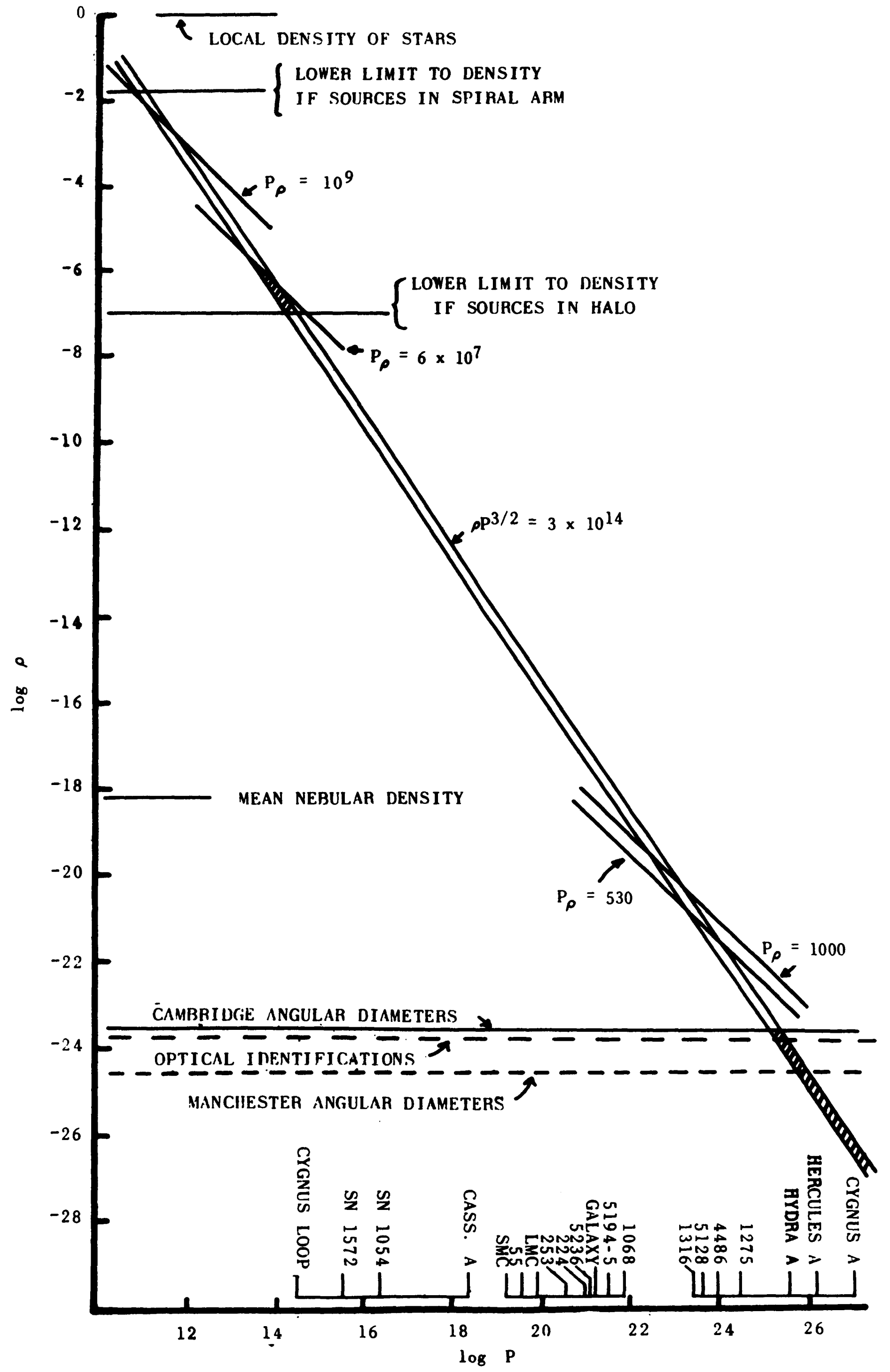

FIG. 1. The line $\rho P^{3/2} = 3 \times 10^{14}$ represents possible values of the space density ρ and the radio luminosity P, which would satisfy the source counts. For sources within the Galaxy lower limits to the density are set by the observed isotropy of the sources, and upper limits are set by the contribution of the sources to the integrated emission. Measurements of angular diameter and evidence from optical observations allow upper limits to the density to be established for extragalactic sources. The black areas on the line $\rho P^{3/2} = 3 \times 10^{14}$ represent the permissible ranges of P and ρ.

Most of the sources might belong to a very numerous class distributed throughout the spiral arm; alternatively, they might be more powerful sources distributed throughout the galactic halo. If observations show N sources per unit solid angle uniformly in all directions, then a lower limit to the space density is given by: $\frac{1}{3}\rho r_1^3 \not< N$, where r_1 represents the smallest distance to the limit of the local spiral arm or halo.

An upper limit to ρ may also be established for these two possible models, by considering the sources' contribution to the background radiation. Observations of the angular distribution of the background emission have made it possible to determine the average emission per unit volume within the spiral arms, within the halo and in extragalactic space [2]. Part of the emission may be caused by radio sources and part by a "continuous" mechanism, but it is clear that the contribution of the sources $P\rho$ cannot exceed the figure required to explain the background emission.

The latter argument may also be used if most of the sources are extragalactic; an upper limit can be derived for $P\rho$ from the maximum value of the integrated extra-galactic radiation; in this case the value depends on the cosmological model adopted [3, 4].

We must now examine the effect of a spread in P rather than the unrealistic model so far assumed. A luminosity dispersion would lead to an earlier appearence of anisotropy and a relatively greater contribution to the integrated emission. It is difficult to know what dispersion to assume, but the luminosity of the identified galactic sources has been found to extend over a range of $10^4 : 1$; for the extragalactic sources the spread is $10^8 : 1$ and even for the seven "abnormal" extragalactic sources the spread is nearly $10^4 : 1$.

It thus seems fairly certain that the spread is likely to be at least $100 : 1$, and we will use this figure in computing the possible ranges of P and ρ using the results available from present surveys. The main radio source surveys we have used are the Cambridge survey on 3.7 m [5], the Australian survey on 3.5 m [6], and the more recent Cambridge survey on 1.9 m [7]. Because some of the detailed observations of the background radiation have also been made at 3.7 m, the numerical data for P are expressed in terms of the emission at this wavelength.

The results are shown in Fig. 1; the width of the line $\rho P^{3/2} =$ constant corresponds roughly to the uncertainty in establishing the number-intensity counts from different surveys and using different methods of analysis. The two upper horizontal lines represent the lower limits to the space density for sources within the spiral arms and for sources in the galactic halo as determined from measurements to detect anisotropy using the results of the 1.9-m survey.

The upper two lines of $P\rho =$ constant represent the corresponding limits set by the maximum permissible contribution to the integrated emission. Similar figures for the extragalactic case represent the maximum contribution permitted by (a) a steady-state cosmological model and (b) a relativistic model of zero space curvature.

It may be seen that we can no longer suppose that most of those observed are weak and numerous sources distributed throughout the spiral arm, and there is only a limited range within which sources distributed throughout the halo might lie; if a spread of 1000 : 1 in the luminosity had been assumed, this possibility would also have been excluded.

It therefore seems probable that most of the sources are extragalactic, and that their luminosity must be considerably greater than that of the Galaxy ($P = 10^{21}$ watts $(c/s)^{-1}$ $ster^{-1}$). If it is supposed that any such objects have a physical extent and an optical luminosity comparable with those of the Galaxy, further restrictions are imposed by the measurements of angular diameter and by the failure to identify most sources with objects brighter than about 18th magnitude [8]. Further arguments [1], based on the difficulty of supplying sufficient energy to maintain the radio emission, confirm the difficulty of accounting for either possible galactic class, and also suggest that in the extragalactic case masses comparable with that of the Galaxy must be involved.

For objects having diameters of the order of 20 kiloparsecs, the recent Cambridge measurements of angular diameter indicate minimum distances of the nearest unidentified sources of about 30 megaparsecs, and hence upper limits of the space density of about 3×10^{-24} $parsec^{-3}$.* The observations made at Jodrell Bank with greater resolving power [9] showed a very much smaller limit to the angular diameters of a few sources; if further observations show that most of the sources have such diameters, the space density must be lower than about 2×10^{-25} $parsec^{-3}$.

It therefore seems very probable that most of the radio sources belong to a class for which $P > 3 \times 10^{25}$ watts $(c/s)^{-1}$ $ster^{-1}$, a figure comparable with the luminosities of the three powerful colliding galaxies in Hydra, Hercules, and Cygnus.

If further observations confirm the present conclusions, the contribution of radio observations to cosmology will become of great importance. For $P > 3 \times 10^{25}$ watts $(c/s)^{-1}$ $ster^{-1}$, the reliable limit of detection even of existing surveys corresponds to an appreciable red-shift. For example, according to the steady-state model, the number of faint sources near the limit of reliable detection of the 1.9-m survey, should be less than that expected according to a static Euclidean universe, by a factor of about 3; the numbers actually observed were *greater* by a factor of about 2. In the Australian survey, the steady-state model would indicate a deficit of 3.4 : 1, whereas again a slight excess was found. Although such comparisons are limited by the poor statistics of the intense sources that can be assumed to have suffered little effect from the red-shift, the arguments presented here suggest that the discrepancy between observation and the predictions of the steady-state model are considerably greater than could be established hitherto [10].

The results are not yet conclusive, and more extensive observations are now awaited; a new radio telescope with a greater resolution and sensitivity

* This result is confirmed by the measurements of angular diameters with the Nançay interferometer, reported by Boischot [12].

than any previous instrument is now in use at Cambridge and should provide reliable observations to greater distances. More extensive measurements of the angular diameters, and further analysis of the optical observations may allow the arguments used here to be developed further. In addition it may be possible, by observation of the 21-cm line in absorption [11], to measure the distances and hence establish directly the radio luminosities of an appreciable number of sources.

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Discussion

McVittie: What is the physical meaning of the distance r—which you first defined as Euclidean distance—when you move over to the steady-state or relativistic models?

Ryle: The scale is basically a luminosity distance, based on an assumed spectrum similar to that of the Cygnus and other sources.

G. R. Burbidge: Could you say something more about the energy requirements if one supposes that the sources are galactic halo objects? How difficult do you believe it is to do this satisfactorily?

Ryle: The difficulty of accounting for the supply of energy to a galactic model for the radio sources is based on the observed limits of angular diameter, which together with the space density, set an upper limit to the physical dimensions of the source. This in turn determines the minimum volume emissivity within the source, and adopting the synchrotron emission mechanism sets a lower limit to the energy stored within each source in the form of magnetic field and high energy particles. While supernova outbursts are capable of supplying adequate energy, such an explanation can clearly not be used for most of the sources. The possibility that enough energy is supplied by collisions between the gas clouds would require unreasonably high gas densities (even if the clouds have velocities near that of escape from the galaxy).

Hoyle: Is it the case that there is still an energy difficulty with halo sources, if we suppose them to be tight knots in a magnetic field?

Ryle: It seems to me that the energy stored in the "knots" of an extended but tangled magnetic field in the halo would still present a difficult problem, but perhaps the energy could be supplied from the rest of the field.

Minkowski: Which fraction of the sources could be in the halo of a galaxy?

Ryle: A mixture of galactic and extragalactic sources has only a small effect on the limits derived; if, for example, half of the sources within a given range of flux density were extragalactic, it would only be necessary to lower the line $\rho P^{3/2}$ = constant by a factor of two, and the conclusions would not be greatly affected. It would certainly be possible for a small proportion of the sources to be within the Galaxy as long as they do not violate the conditions discussed on the appropriate lowered line $\rho P^{3/2}$ = constant.

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