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INSA VAINU BAPPU MEMORIAL AWARD LECTURE—1987

RADIO GALAXIES, QUASARS AND COSMOLOGY

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INTRODUCTION

I AM honoured and delighted to receive INSA's Vainu Bappu Memorial Award and Medal today.* I had the privilege of knowing Vainu Bappu for over two decades and was greatly inspired by his zeal and dedication towards astronomical research. He was also a brilliant lecturer, but I must admit that it would be difficult for me to emulate him.

I plan to address myself today to the problem of the origin and evolution of the Universe as seen through the radio window. The great discoveries of radio galaxies made by radio astronomers during 1950's, of quasars (quasi-stellar radio sources) in 1963 and of the 2.7 K Cosmic Microwave Background Radiation in 1965 have made a dramatic and revolutionary impact on the understanding of our Universe. In particular, these observations have provided a strong support to the Big Bang Model, according to which the Universe originated about 15 billion years ago from an extremely dense condensate and has been expanding ever since.

In recent years there has also been rapid progress in the field of extragalactic astronomy through the exploitation of the optical, infrared and X-ray windows. Thus, a wide variety of active galactic nuclei (AGNs) have been reeognised: ranging from mildly active to extremely active phenomena, such as Star-burst Galaxies, Seyferts, Radio Galaxies, Quasars/QSOs, Blazars, etc. Another major input to observational cosmology has come through the determination of the abundances of primordial elements in the Universe, particularly those of helium, deuterium and lithium. Further, both radio and optical observations indicate that over 90 per cent of the matter in the Universe is grossly underluminous. The presence of this 'dark' component of matter can be inferred, nevertheless, from its gravitational effects on the visible matter, e.g. from the rotation curves of galaxies. Finally, one must explain not only the clustering of galaxies, but also the observed large-scale structures, such as seen in the form of super-clusters of over 100 million light years across.[1] Even more difficult is to explain the recent observations of large-scale foamy or spongy structures in the galaxy distribution bordering great voids.[2] Many theorists believe that most of these observational features could

*Lecture delivered at INSA's annual meeting held at the University of Poona on January 6, 1988. The manuscript was received from the awardee in August 1988.

have originated in the very early phase of the Universe soon after the Big Bang, when the Grand Unification Theories (GUTs) and the quantum gravity are likely to have played an important role.

In my talk today, I plan to confine to the evidence provided by radio astronomy about the origin and evolution of the Universe. After a brief description of radio galaxies and quasars, I plan to discuss the counts of radio sources, deep optical identifications, luminosity functions, and angular size cosmology. I would also describe the recent work by our group concerning linear size evolution of radio galaxies and quasars. Finally, I propose to discuss briefly our plans for the construction of a Giant Metrewave Radio Telescope. One of its major objectives would be to search for the clouds of neutral hydrogen gas that eventually condensed to form galaxies.

Radio Galaxies and Quasars

A radio galaxy or quasar usually appears as a pair of radio-emitting lobes situated on the opposite sides of an optically luminous giant elliptical galaxy, at a separation of a few hundred kiloparsecs or less (1 kpc = 3261 light years) (Fig. 1). Often a compact radio source, called central component, is seen coincident with the parent galaxy located between the radio lobe pair. In many cases, jet-like radio features have been detected which emanate from the central component towards one or both the radio lobes. The jets are found to be quite prominent in nearby, low-luminosity sources ($P_{408} < 10^{26}$ WHz^{-1} at 408 MHz). The energy radiated by a powerful radio galaxy is indeed enormous and is generally believed to have a gravitational origin. Possibly, pair-plasma is produced during the accretion of matter on to a massive Black Hole of about 10^{8-10} solar masses, located in the nucleus of the active galaxy.[3] The plasma escapes along the rotating axis of the central engine, resulting in a pair of jets transporting relativistic particles outward in two opposite directions. The jets are counteracted by the ram pressure of the intergalactic medium so that randomized relativistic particles are produced at the tips of the two jets. This gives rise to a double radio source radiating by the synchrotron mechanism in the presence of weak magnetic fields ($10^{-4} - 10^{-6}$ G). It is found that most of the powerful radio sources are associated with the brightest elliptical galaxies having nearly the same absolute optical magnitude ($M_v = -23$). Over 20,000 radio galaxies have been catalogued to date.

Quasars were discovered in 1963; Cyril Hazard identified the strong radio source 3C 273 with a compact star-like object based on lunar occultation observations made with the Parkes radio telescope in Australia. Maarten Schmidt made a brilliant deduction that the object had a high redshift, $z = 0.158$ (Fig. 2). The optical luminosity of many quasars is extremely high, being about 100 times larger than that of the brightest known galaxy. Yet, the gas clouds emitting broad optical emission lines as well as encompassing the central engine extend no more than a few light years across. Over the last two decades, quasars have been studied over a wide range of wavelengths from radio to X-rays. The radio-

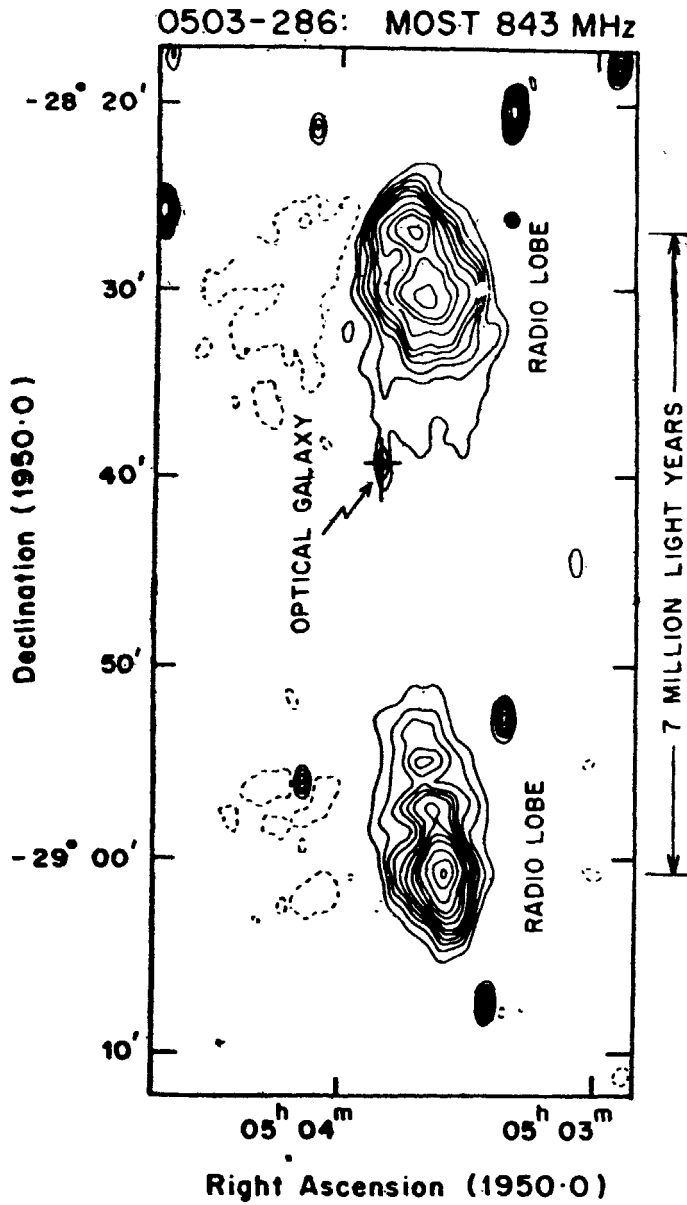

FIG 1 A radio map of a giant radio galaxy discovered by Subrahmanya and Hunstead[61] using Molongolo Radio Telescope (and independently by Saripalli *et al.* (1986)[62] using Ooty Synthesis Radio Telescope. The distance between the two outer radio lobes is about 2.5 Mpc. A weak central radio component is coincident with the optical galaxy.

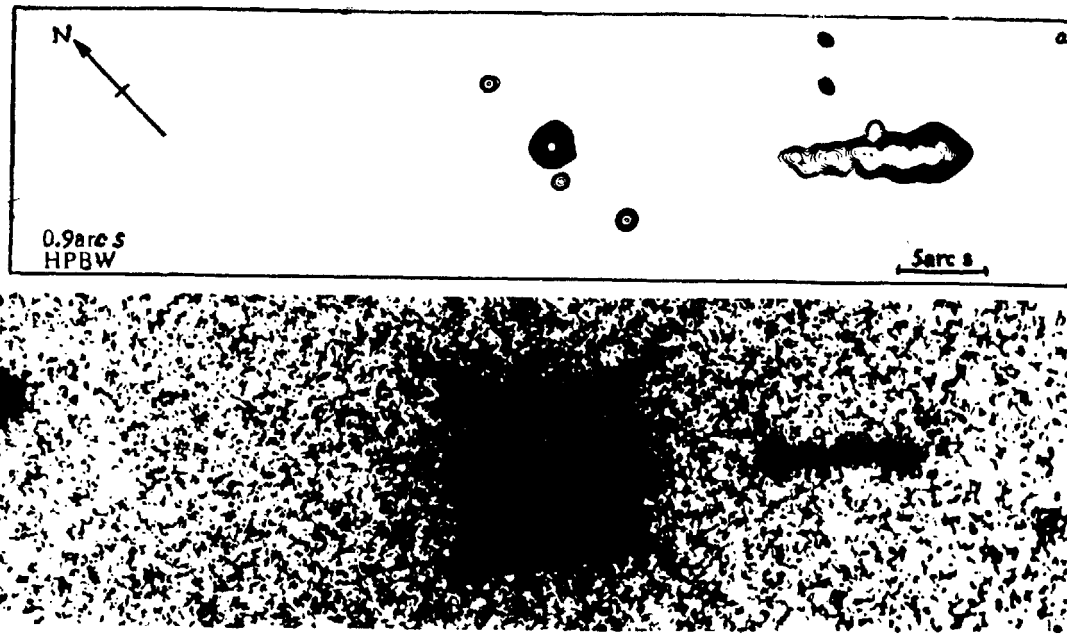

FIG 2 The upper picture is a radio map of 3 C 273 showing a central component and a long radio jet made by Conway *et al.*,[81] using MERLIN in U. K. The lower picture is an optical photograph.

emitting quasars seem to be a small subset of a parent population referred to as QSOs (Quasi-stellar objects). Most of their X-ray and UV radiation is likely to arise thermally from hot plasma near the accretion disk around the black hole.[4-6] The optical continuum is perhaps reprocessed by the surrounding gas. The narrow emission lines seen in the quasar spectra arise from numerous cloudlets located at distances upto about 1 kpc from the active nucleus. The broad emission line region is only about 1 pc in size.

About 3000 quasars have been catalogued so far.[7] Only about 10 per cent of the quasars discovered from optical surveys are found to have a substantial radio output. These radio-loud quasars are of two types : characterised by flat or steep radio spectrum; the former are perhaps relativistically beamed towards us.[8,9]

In view of their high redshifts, quasars can serve as valuable probes for investigating whether some properties of the Universe have changed with its age. The optical spectra of many quasars show highly redshifted absorption lines which are likely to be caused by intervening galaxies or intergalactic clouds. Studies of absorption lines have provided extremely valuable data for cosmological studies. Equally exciting are the discoveries of several quasars, each appearing as a close double (or triple) image, with identical redshifts for the images. These multiple images are believed to arise due to gravitational lensing by intervening galaxies as well as by clusters of galaxies. There are now more than ten possible

gravitationally lensed quasars, of which at least 4 are generally accepted as lensed candidates.[10] One of the strongest flat spectrum radio sources in the sky, 1830–211, has been shown recently by the Ooty group to be a double source with 1 arcsec separation[11] and is likely to be a very interesting gravitationally lensed quasar. Studies of such gravitationally lensed quasar can provide important information about the nature of dark matter in galaxies and clusters and about the geometry of the Universe.

Radio Source Counts

By mid-1950 when only about 17 radio sources were identified optically and distances were not known even for most of them, Martin Ryle of Cambridge made a remarkable suggestion that a plot of integral number counts, $N(>S)$, of radio sources against flux density, S, can be used to distinguish between the two rival hypothesis, the Steady State and the Big Bang models of the Universe. Since $N \propto R^3$ and $S \propto R^{-2}$, where R is the distance of a radio source, we expect $\log N (>S) - \log S$ curve to have a slope of -1.5 in an Euclidean Universe. The steeper slope of -1.7 found by Ryle suggested a higher co-moving density of radio sources at earlier cosmic epochs, supporting the evolutionary scenario.

Since integral counts suffer from cumulative errors, radio astronomers prefer to plot differential source counts : $\log (N/N_0)$ versus $\log S$, where N_0 is the expected source count at a flux density of S for a Euclidean geometry. Due to several high resolution surveys made over the last decade, accurate radio counts are now available over a wide range of flux densities at several frequencies from 327MHz to 5 GHz.[13,14] Fig. 3 (*a*) shows a plot of $\log (N/N_0)$ versus log S at 1415MHz for a flux density range of about 0.1 m Jy to 10 Jy (1 Jy = 1 Jansky = 10^{-26} $Wm^{-2}Hz^{-1}$) and is based on many surveys including several deep surveys made at Westerbork.[14,15] In Fig. 3(*b*) we have plotted source counts by Subrahmanya and Mills[12] made at 843 MHz using Molongolo radio telescope *alone*. The data of 1415 MHz and 843 MHz, when superimposed, show a remarkable agreement. In order to illustrate this agreement, a polynomial fit to the data at 1415 MHz is superimposed onto the data at 843 MHz.

The broken line curve in Fig. 3 (*a*) indicates approximately the expectation of the source counts in a Friedmann cosmology (Fig. 17 of Longair 1978.[16]) The source counts are expected to converge rapidly for weaker and more distance sources due to the expected decrease in volume element and also a decrease of flux density with increasing redshift in an expanding Universe. This rapid convergence also holds for the Steady State Model. Thus, the radio source counts support an evolution of the space number density and/or luminosity of radio sources, as discussed in section 5 below.

The deep surveys made at 1415 MHz at Westerbork (Fig. 3*a*) indicate that the source counts tend to rise again or at least flatten at $S < 10$ mJy, with the 'excess' becoming more prominent at $S <$ 1mJy. This upturn cannot be produced by the evolving population of radio sources that dominates the counts at higher

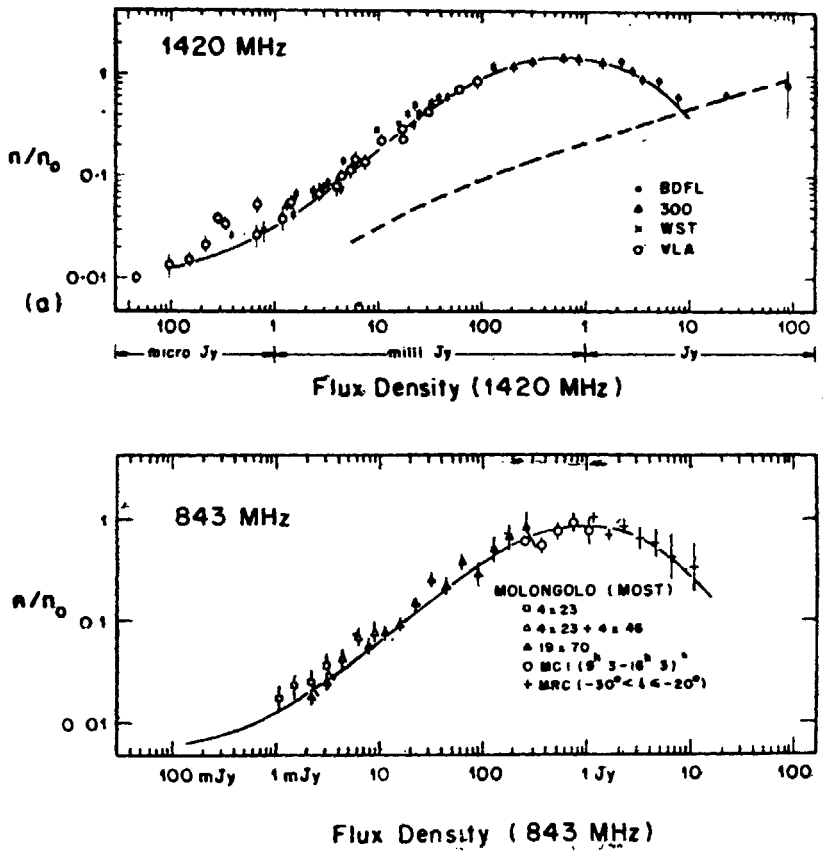

FIG 3 Normalized source counts, (N/No), at 1420MHz are plotted against flux density in the upper figure[14,15]; those at 843MHz are plotted in the lower figure.[12] The solid line is a polynomial fit to the 1420MHz data and the same is then superimposed on the 843 MHz data.

flux densities. The sub-mJy population is likely to arise mainly due to the relatively nearby population of radio sources. However, there is considerable uncertainty concerning their nature. While both Subrahmanya (see Windhorst)[18] and Wall *et al.*[12,17] suggest that the radio-weak, non-evolving population of spiral and SO galaxies could account for the upturn, Condon[19] attributes it to an evolving spiral galaxy population implying a high redshift for the sub-mJy sources. On the other hand, Windhorst *et al.*,[20,21] Windhorst[18] and Oort[14] identify the upturn with an evolving population of blue radio galaxies and Danese *et al.*[22] with starburst/interacting galaxies. In order to resolve this controversy, one needs to determine the local luminosity functions of various classes of galaxies more accurately. This is being attempted by Subrahmanya and others.

A complete sample of 59 radio sources with flux densities lying between 1 and 2 Jy at 408MHz has been selected by Allington-Smith[23] from the Bologna

catalogue and mapped with the Cambridge radio telescope. Parent galaxies of these sources have been identified at a wavelength of 2.2 μm using the UK Infrared Telescope at Hawaii.[24] This way, one is able to sample the most distant giant ellipticals near the maximum of their spectral energy distribution. Fig. 4 shows the estimated redshift distribution for the 1-Jy sample.[24] These observations indicate that the radio galaxies may have a redshift cut-off at about $Z = 3$ or less which is consistent with a similar conclusion reached by Windhorst[25] from a detailed analysis of the radio source counts.

The optically selected quasars also show considerable evolution in their space density and/or luminosity. Recent discoveries of six high redshift quasars with $Z > 4$ have extended our astronomical horizon considerably.[26,27] These searches were based on a multi-colour technique. It is intersting to note that 3 out of the 6 quasars were actually found in a single UK-Schmidt telescope field. The most distant quasar, 0051-279, has a redshift of 4.43 and its radiation started when the Universe was only about 10 per cent of its present age. Based on earlier unsuccessful searches for high redshift quasars, it was believed that the space density of quasars may be decreasing beyond a redshift of about 3.[28,29] However, the recent detection of several quasars at $Z > 3.5$ seems to indicate that the space density of

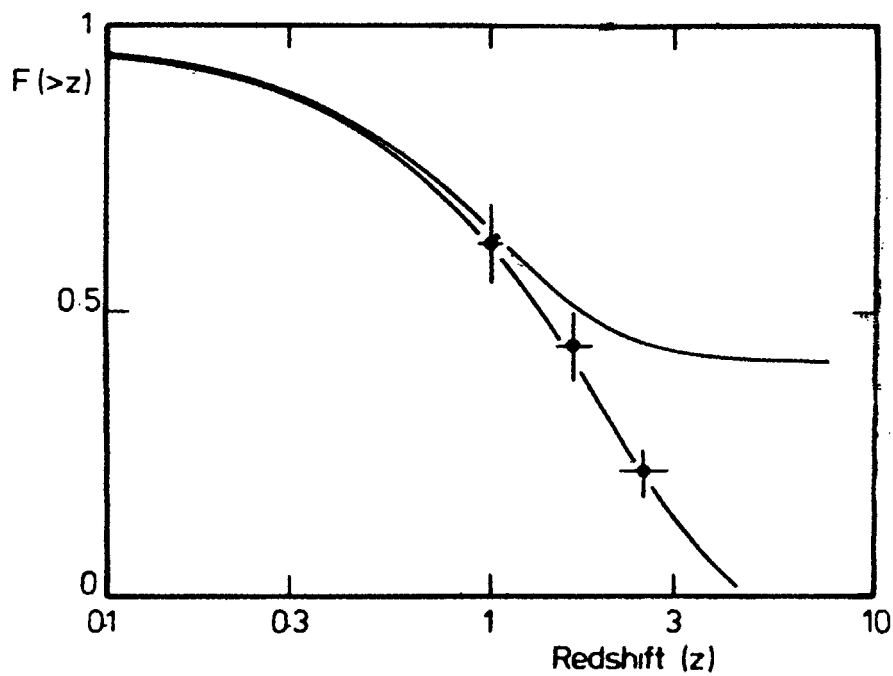

FIG 4 Comparison of the cumulative redshift distribution of sources in the '1 Jy' sample, as shown by the three points, with predictions derived from Peacock's representations of the epoch dependent radio luminosity function; the two solid lines show the uncertainty of the representations.[24]

bright quasars may still be increasing towards such high redshifts,[30,31] although at a much reduced rate than that upto redshifts $Z \sim 2$.

Deep Optical Identifications

For interpreting the source counts, we firstly need to determine the luminosities of radio sources forming a nearby, i.e., local, complete sample. Since the radio data do not provide a measure of distance, it is determined by finding the redshift of the optical object coincident either with the central component of the radio source or, alternatively, with its radio centroid. Although optical identifications are now available for a few thousand radio galaxies, the measurement of redshift has been accomplished for only a few hundreds of them. In most cases, the enormous distances render the optical counterpart very faint.

For investigating the evolution of radio galaxies with cosmic epoch, it is important to restrict to samples that are complete above a certain flux density limit at a given frequency in a particular region of the sky. The most extensively studied sample is the 3CR-LRL list consisting of 173 strong radio sources over a 4.2 steradians of the northern sky, with $S_{178} \geqslant 10$Jy.[32] The identifications and redshift determination for these bright radio sources have been pursued vigorously over the last 20 years mainly by Longair and his collaborators in UK and Spinrad and collaborators in USA, initially using an image tube and later a CCD Camera fitted on the 5-metre optical telescope at Mt. Palomar. About 97 per-cent sources in the 3CR-LRL sample are now optically identified. In Fig. 5 is shown redshift distribution for the sample of 3CR sources studied by Laing *et al.*,[32] the redshifts ranging upto about 1.6 for radio galaxies and about 2.1 for quasars. Over 90 per cent complete identifications and four-colour magnitude measurement are also available for a sensitive survey of weak radio sources made at Westerbork.[14,20] They provide valuable information about the cosmic dependence of radio source properties.

Radio Luminosity Function and Its Evolution

Determination of the radio luminosity function (space densities of radio sources of different luminosities) and its evolution with cosmic epoch has been a daunting task, entailing numerous investigations over the last two decades. Although a clear picture seems to be now emerging, a lot more work remains to be done. The first step is to find out the local luminosity function (LLF) using redshift data for nearby radio sources. The next step is to determine whether there has been any statistical increase in either density and/or luminosity of radio sources as a function of redshift. The evolution function may be different for radio sources of different luminosities. There is also likely to be a redshift cut-off, which gives information about the era when radio galaxies and quasars began to form in the course of evolution of the Universe. By combining the radio source counts over a wide range of flux densities and frequencies with redshift data and the identification data for different samples, it has been shown by several workers[33–35] that radio sources were very much brighter and/or their space density was higher by a

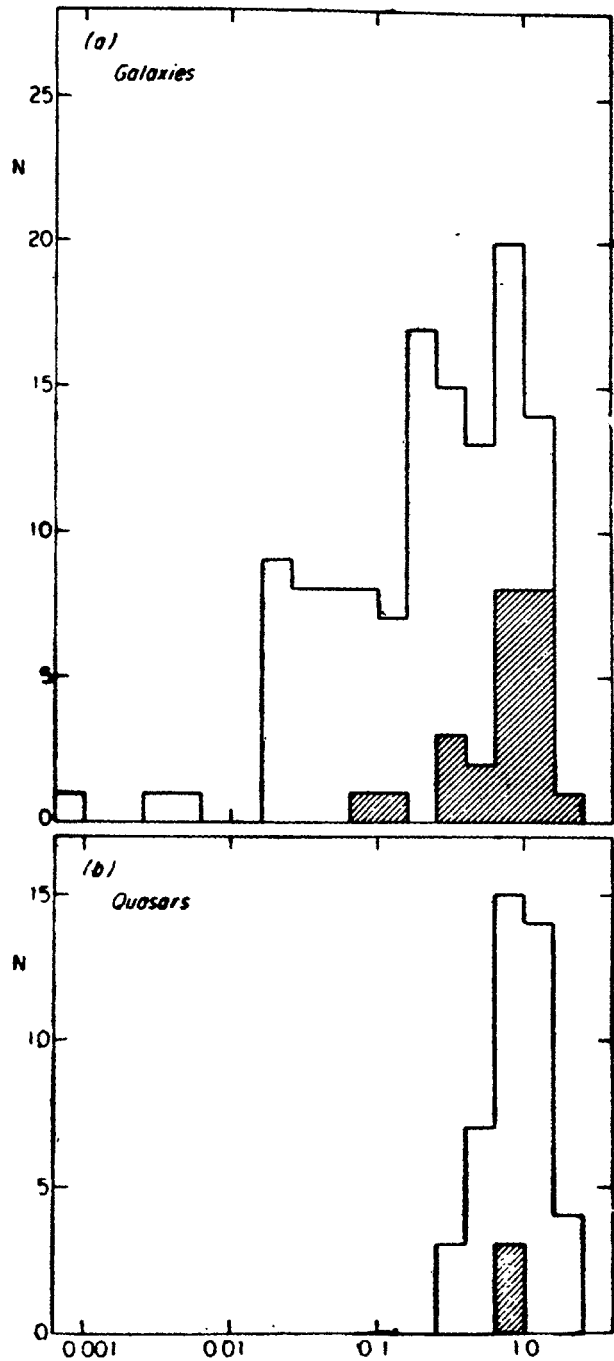

FIG 5 Redshift distribution for a sample of 3 CR sources[33]. Shaded portions show redshifts estimated from magnitudes.

factor of about 1000 in the past than today. Fig. 6 shows estimated variation of the evolution function with redshift for steep and flat spectrum radio sources.[34]

Angular Size Cosmology

In a Euclidean space, the angular size of a rigid rod is inversely proportional to its distance. However, due to the curvature of space in the Universe, the variation of angular size with redshift depends on the world model for the curvature. A test is difficult in optical astronomy because the isophotal diameter of a galaxy depends on its apparent magnitude.[36] In contrast, the separation between the outer lobes of radio sources may provide a metric diameter as it is not so critically dependent on the sensitivity of observations and may be used for testing the world models.[37] From an essentially random sample of quasars, Miley[38] found that $l \propto Z^{-1}$ contradicting the predictions of all world models incorporating uniform density. Fig. 7 shows a recent $l - Z$ plot for quasars as well as for radio galaxies.[39] The observations thus indicate that the physical sizes of radio sources were systematically smaller at higher redshifts. A size evolution of the from $l \propto (1 + Z)^{-n}$, with $n \sim 1$ to 2, provides a good fit to the data. It has been argued, however, that a possible anti-correlation between linear size and radio luminosity may explain the observed $l - Z$ relation because in a flux-density limited sample, sources located at higher redshifts are also expected to have higher luminosities.[40–42]

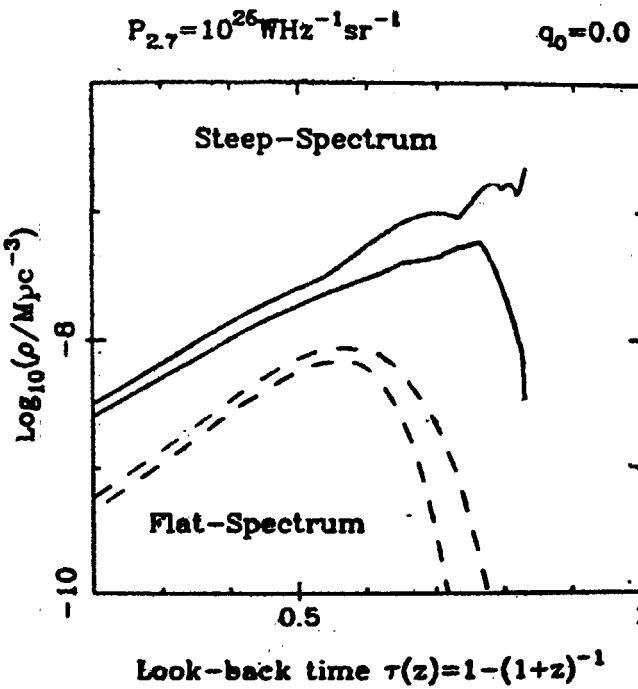

FIG 6 The evolution of the Radio Luminosity function, ρ, plotted against the look back time, τ, normalized to the age of the Universe.[34]

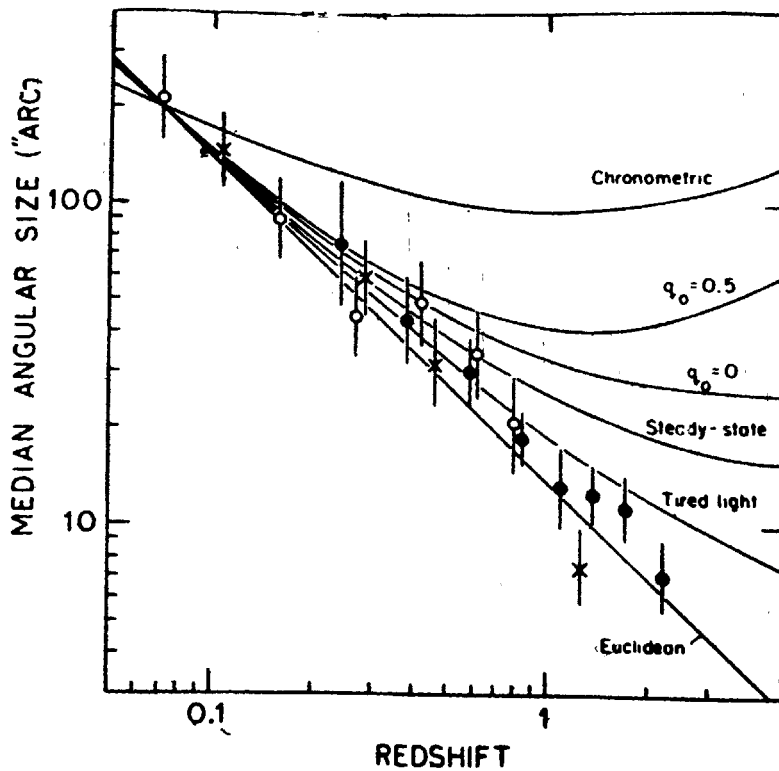

FIG 7 Prediction of several world models compared with the observed θ_m-Z relation.[29] θ_m values for galaxies are shown by open circles and for quasars by filled circles. Crosses show θ_m values for 4 samples of nearly same radio luminosities.[30]

The Ooty Radio Telescope was constructed during late 60's[43] for measuring angular sizes of a large sample of weak extragalactic radio sources using the method of lunar occultation. These observations established an angular size (θ)–flux density (S) relation for the first time, indicating that the median value of θ decreases from about 100 arcsec for the nearby strong 3C sources to about 10 arcsec for the weaker extra-galactic radio sources.[44] Using $N(S)$ and $\theta_m - S$ relations, it has been shown that not only radio sources had a higher number density but their linear sizes were also smaller on average, at earlier cosmic epochs.[45] Subsequently, θ_m–S relation has been investigated independently by a number of workers.[46,47,48] Recently, it has been extended to much lower flux densities as shown in Fig. 8, where θ_m is found to decrease to about 1 arcsec for $S_{1415} < 10$ mJy due to the emergence of a new population of blue radio galaxies at lower flux densities.[14,15,49,50]

In order to take into account any possible anti-correlation between luminosity and linear size, Downes *et al.*[51] used individual sources in the well-observed 3CR sample to estimate the contribution of sources of that luminosity to the number and θ distribution in a given range of S for assumed models of radio luminosity

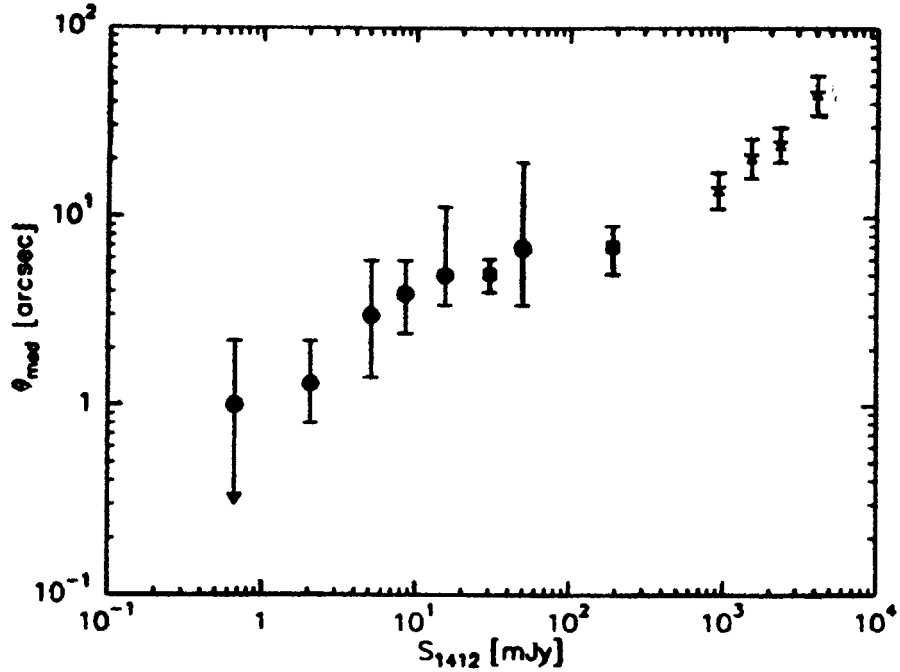

FIG 8 The median angular size is plotted against flux density of radio sources.[14]

evolution, and concluded that the size evolution was not required. Similar conclusions were reached by Downes[52], Fielden *et al.*[53] and Allington-Smith.[54] However, a more comprehensive analysis by Kapahi *et al.*,[55] employing samples of strong sources selected at appropriately different frequencies and considering several evolutionary models has clearly established the need for linear size evolution (Fig. 9).

Recently, Kapahi[56,57] has shown unambiguously that radio galaxies were physically smaller at higher redshifts, by studying 3 samples of radio galaxies having nearly the *same* range in radio luminosity ($10^{25.7} < P_{1415} < 10^{27.1}$ WHz^{-1}) but widely different redshifts. Assuming linear size evolution of the from $l \propto (1 + Z)^{-n}$, he found that $n \sim 1$ to 2. Kapahi[57] also found that there exists a weak $P-l$ correlation of the form $l \propto P^{0.25 \pm 0.1}$ for radio galaxies at nearly same redshift, in conformity with some earlier results.[58,59] By comparing a sample of 67 radio sources from the weak 6C survey at 151 MHz with the 3CR strong source sample at 178 MHz, Eales[60] also found that $n = 1.45 \pm 0.4$ for constant luminosity. Oort[14,15] and Oort *et al.*[49,50] have arrived at a similar conclusion using faint Westerbork source samples having nearly complete optical identifications, but their best-fit to the data is attained for $n \sim 3.3$ and $l \propto P^{0.3}$ at the same redshift (for radio sources with $P_{1415} < 10^{27}$ WHz^{-1}). They also considered FRI type of radio sources with $P_{1415} < 10^{26}$ WHz^{-1}). Singal[61] has studied a sample of 669 optically identified extragalactic radio sources, compiled from a number of published sub-samples and has inferred $n \sim 3$ for $10^{26} < P_{408} < 10^{27}$ WHz^{-1}.

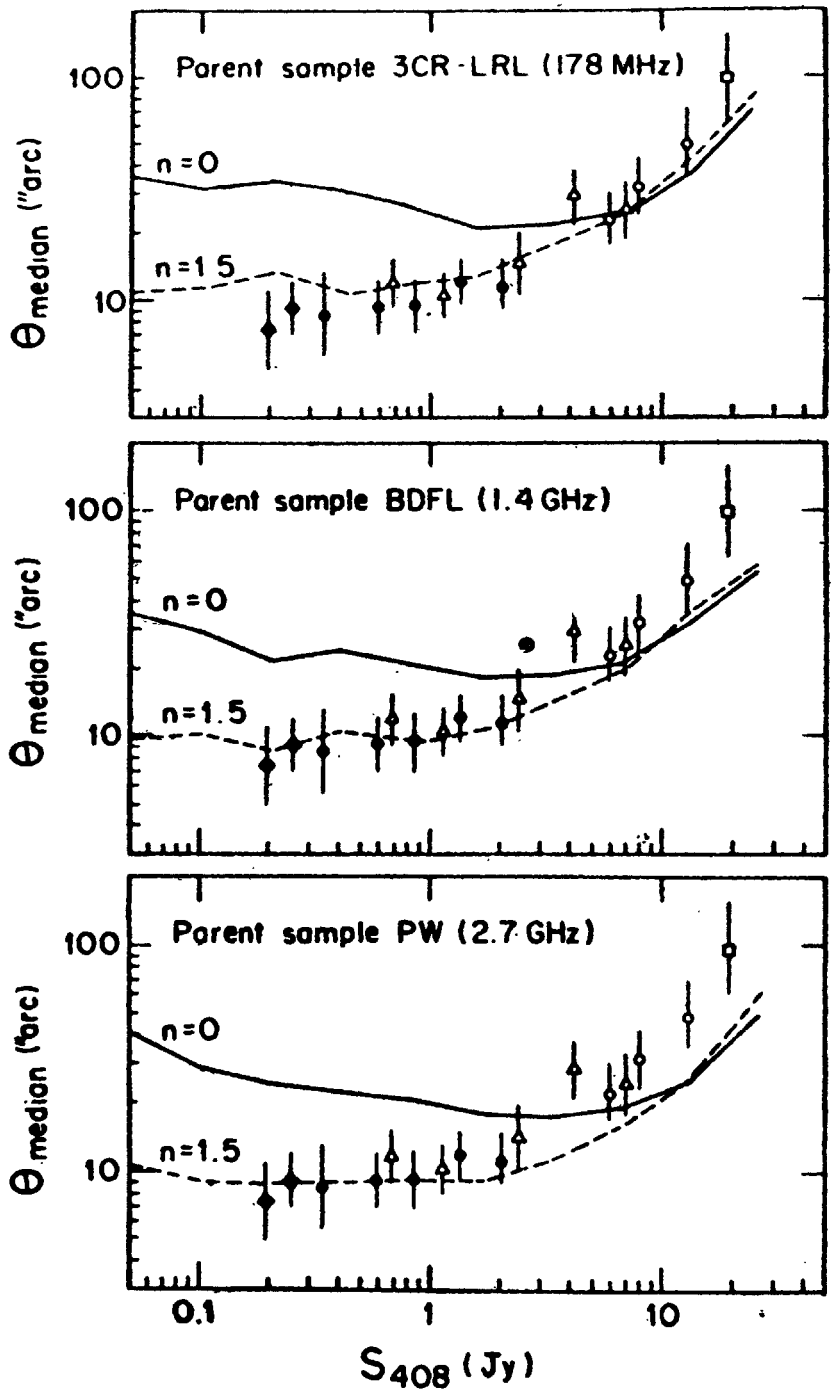

FIG 9 Predictions of the Subrahmanya and Kapahi[35] (1983) evolutionary model using parent samples at different frequencies are compared with the observed data.[55]

In Fig. 10 we have compared median values of linear size, l_m, against redshift for samples of radio galaxies considered by Kapahi[39,45,56,57] ($10^{25.7} < P_{1415} < 10^{27.1}$ WHz^{-1}), Oort *et al.*[49,50] ($10^{26} < P_{1415} < 10^{27}$ WHz^{-1}) and Singal[61] ($10^{26} < P_{408} < 10^{27}$ WHz^{-1}). Kapahi[57] has only given values of θ_m, but we have converted these values to l_m assuming $H = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$. It is seen from Fig. 10 that all the above samples show similar linear size evolution. However, Oort *et al.* s[49,50] values of l_m are $\sim$ 1.4 times lower than those of Kapahi observed at the same frequency (1415MHz) and in almost the same luminosity range. This could be due to somewhat different samples considered by them. Values given by Singal correspond to 408MHz but are consistent with Oort's values of l_m at 1415 MHz, if we assume spectral index $\alpha = 0.8$ and $l_m \propto p^{0.3}$.

Singal has also determined l_m for very luminous radio sources having $P_{408} > 10^{27}$ WHz^{-1}, and finds that linear size of radio galaxies continues to *increase* with luminosity for the same redshift. From his plots it seems that l_m appears to be independent of Z for the most luminous sources. But, this inference should be considered with caution because his data are incomplete for higher redshifts as he has considered identified sources alone.

In order to investigate the dependence of linear size with radio luminosity at higher redshifts than considered by Singal,[61] we have formed three different sub-samples. The first one consists of thirteen 3 CR radio galaxies having $Z > 1$ from the complete 173 bright source sample with $S_{178} > 10$ Jy given by Laing *et al.*,[32] redshifts for which are taken from Spinrad *et al.*[62] and McCarthy *et al.*[63] The median value of linear size for these 13 sources is found to be $\sim$ 300kpc and the

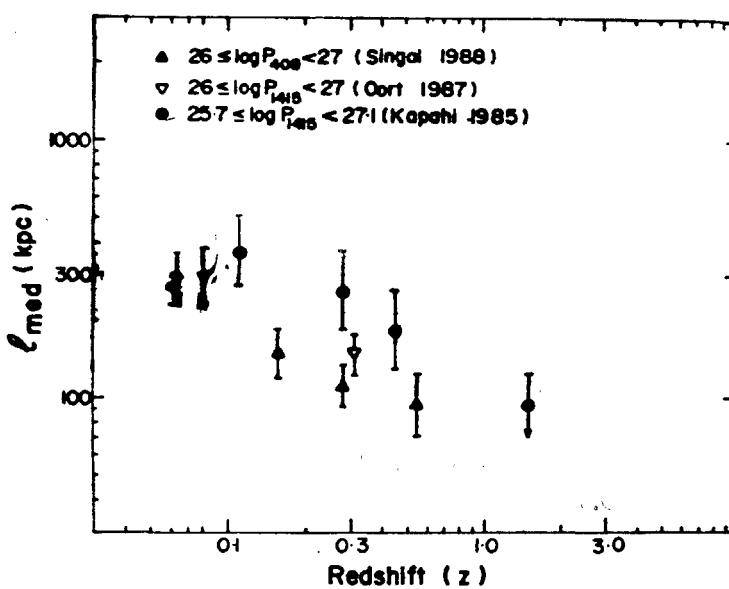

FIG 10 A comparison of the median values of linear size, l_{med}, against red-shift for samples of radio galaxies considered by Kapahi,[56] Oort[14] and Singal.[61]

25 and 75 percentile values are 145 and 480 kpc. The radio luminosities of these sources at 408 MHz lie between $10^{28\cdot8}$ and $10^{29\cdot5}$ WHz^{-1}. There remain 6 unidentified sources in the above 173 bright source sample; the median angular size for these 6 sources is about 23 arcsec. Hence even if all these 6 sources have $z > 1$, l_{med} for the bright source sub-sample with $z > 1$ would still be about $\sim$ 300 kpc. Our second and third sub-samples were formed from the 1 Jy sample of Allington-Smith.[23] It is known that differential radio source counts are nearly flat at 1 Jy at 408MHz, indicating that such sources are likely to be at a fairly high redshift on an average. Lilly *et al.*[24] have made deep identifications and accurate magnitude measurements at near infrared wavelengths (2.2 μm) for the 1-Jy sample of 59 sources studied earlier at radio wavelengths by Allington-Smith[23] and at optical wavelengths by Allington-Smith *et al.*[64,65] From these observations, yielding either direct or indirect yet fairly reliable measure of redshifts, we have determined l_m and Z_m for 19 radio galaxies in the sample with $Z > 1$ and $P_{408} > 10^{28}$ WHz^{-1}; and for 14 sources with $Z < 1$ and $10^{27} < P_{408} < 10^{28}$ WHz^{-1} (out of 59 sources, 13 are quasars; the data are not given for 9 sources and another 4 sources have $P_{408} < 10^{27}$ WHz^{-1}). The median linear size for the fourteen 3 CR sources and 1 Jy sub-samples are plotted in Fig. 11, where we have also reproduced values from Fig. 7 of Singal.[61] We have also plotted the values of Oort *et al.*[46,47] for FRI sources with $10^{25} < P_{1415} < 10^{26}$ WHz^{-1} but have multiplied his l_m values by a factor of 1.4 so as to correspond to 408 MHz luminosity range $10^{25} < P_{408} < 10^{26}$ WHz^{-1}, assuming $\alpha = 0.8$ and $l \propto P^{0\cdot3}$. Finally, in Fig. 11, we have also plotted curves corresponding to the relation $l = l_0 P^{0\cdot3} (1 + Z)^{-3}$, close to that suggested by Oort *et al.*,[49,50] where l_0 has been chosen arbitrarily so as to provide an eye-fit to the data for the range $10^{26} < P_{408} < 10^{27}$ WHz^{-1}. It is seen that all the data are broadly consistent with the above empirical relation. However, a larger data base is clearly required to establish the dependence of l on P and Z more definitively.

Interpretation of the Observed Linear-Size Evolution

The growth of radio lobes of active elliptical galaxies is believed to be sustained by the beams transporting relativistic particles from the nucleus into the lobes. Hence, the size attained by a source will be substantially determined by the influence of the environment on the outward propagation of the beams. One may thus expect a cosmological evolution of linear-size, in case the properties of the environment change with cosmological epoch.

Recent analysis of X-ray observations of massive elliptical galaxies near the edge of the Virgo cluster and some isolated large elliptical galaxies indicates that each galaxy is surrounded by a halo of hot gas ($T \sim 10^7$ K).[66] Further, an analysis of the 5–200 keV X-ray background supports the hypothesis that an even hotter [$T_{IGM} = 2.10^8 (1 + z)^2$ K], lower-density [$n_{IGM} = 7.10^{-7} (1 + z)^3$ cm^{-3}] intergalactic medium (IGM) pervades the Universe.[67] Gopal-Krishna and Wiita[68] have recently developed an analytical model for the beam propagation, first through the galaxy halo and then through the IGM, after crossing the halo/IGM interface. The

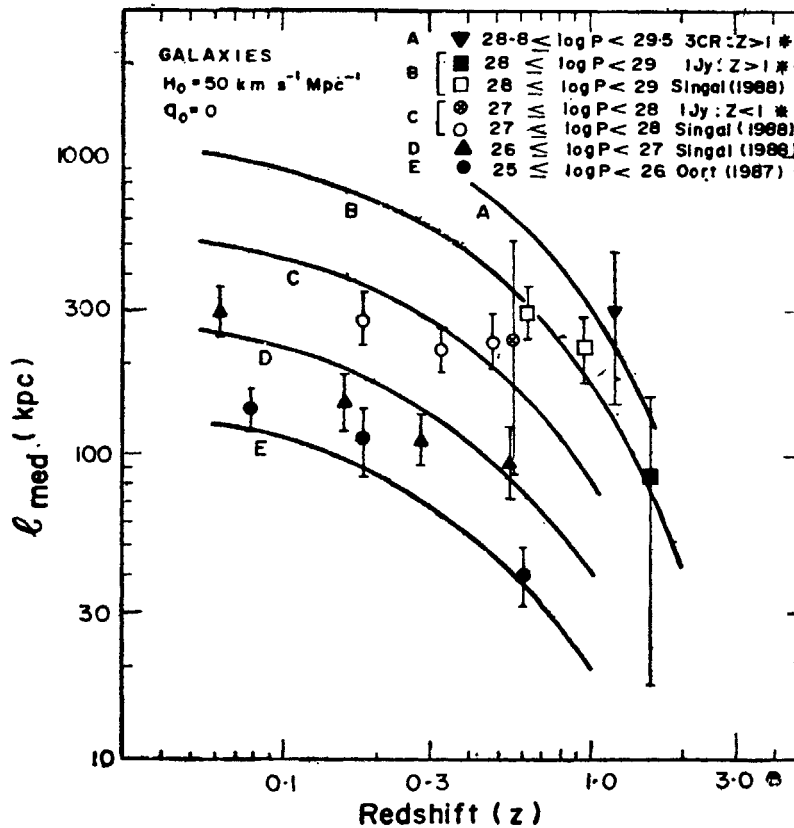

FIG 11 A plot of the median values of linear size with redshift for five different luminosity ranges. Starred luminosity ranges are from present work. The solid curves are theoretical predictions of the model by Gopal-Krishna and Wiita[68] for the above five luminosity ranges.

advance of the beam halts either because of its head decelerating to sonic speed relative to the ambient medium, resulting in decollimation of the beam, or, due to cessation of the activity in the nucleus after some fixed lifetime, say 10^8 years. At higher redshifts, the steep rise in the IGM pressure [$p_{IGM} \propto (1 + Z)^5$] would compress the galaxy halo, so that the halo/IGM interface would move closer to the nucleus. The solutions of the analytic equations for beam propagation then predict a rapid variation of linear-size with redshift [$l \propto (1 + Z)^{-3}$] for a typical source. This analytical result has subsequently been confirmed by computer simulations employing a three-dimensional boundary-following code.[69]

It is interesting that the extremely rapid cosmological evolution of linear-size, as predicted by the above model, has been confirmed by the most recent observations.[46,47,61] Similarly, the observed dependence of linear-size on radio luminosity ($l \propto P^{0.3}$) is also well explained by the model. Moreover, if one makes the reasonable assumption that the pressure inside the haloes of elliptical galaxies was not much higher than the present value, the model predicts galactic sizes for

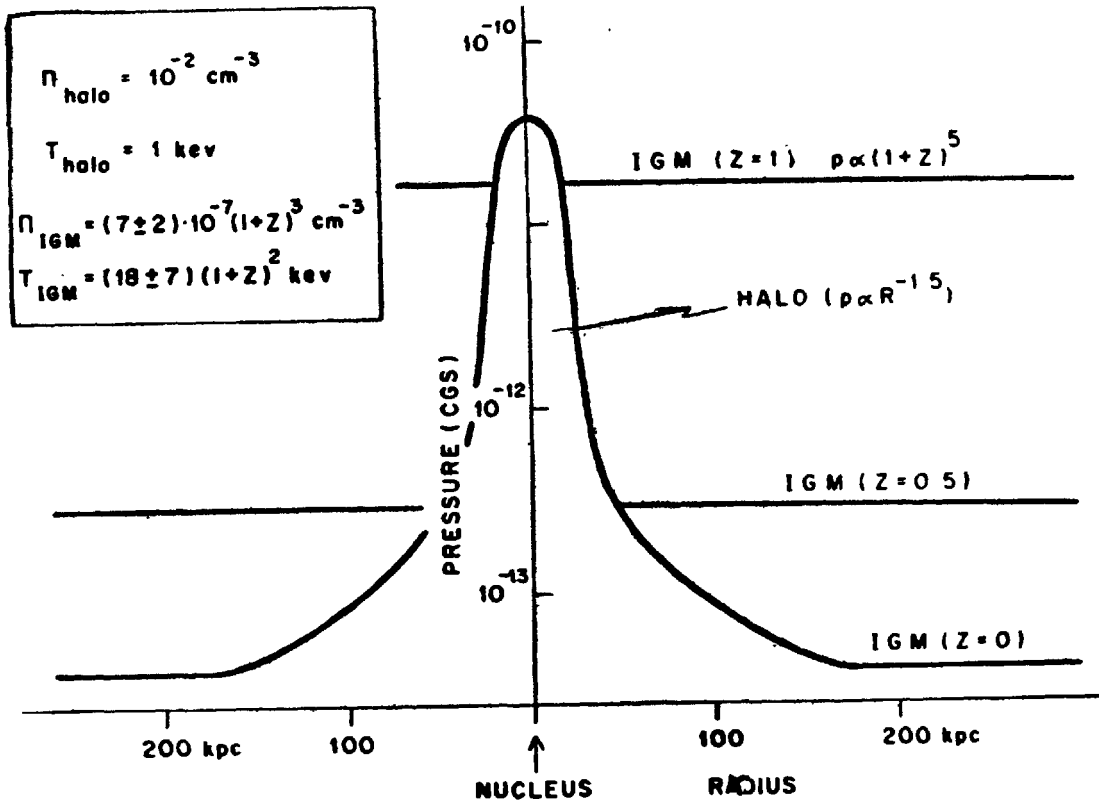

FIG 12 Variation of the pressure of the galactic halo and the intergalactic medium is plotted against radial distance for the model parameters assumed by Gopal-Krishna and Wiita[68] to explain linear size evolution.

typical radio sources, which is in good agreement with the recent observations of high-redshift quasars.[70]

A further consequence of the above approach is that beams with powers below $\sim 10^{25}$ W are expected to be decelerated to sonic speed while they are still to emerge out of the halo, leading to a rapid decay of radio luminosity. This scenario can explain the occurrence of the well-known break in the radio luminosity function of nearby elliptical galaxies, around a luminosity of 10^{24} WHz^{-1} at 1 GHz.[71]

Unless all these agreements with different types of observations happen to be coincidental, the model provides a satisfactory description of the physics of beam propagation in active galaxies and, further, indicates the existence of a cosmologically significant intergalactic medium.

Model by Gopal-Krishna and Wiita[68] is critically dependent on the X-ray background arising due to a hot IGM as proposed originally by Cowsik and Kobetich[72] and investigated in detail recently by Guilbert and Fabian.[67] I would like to suggest an alternative possibility according to which the haloes around ellipticals have a higher pressure at earlier cosmic epoch due to an interplay

between the inflow of gas and the outflow resulting due to the intense star-burst activity at higher redshifts. This possibility is consistent with recent observations of high redshift 3C radio galaxies indicating the presence of dense ionized clouds around the galaxy[63,73] and also the observed smaller sizes of high redshift quasar.[70] One may be able to distinguish between these alternatives by studying the properties of hot spots and radio lobes as a function of luminosity, linear size and redshift.

Evolution of the Universe and Formation of Galaxies

As discussed above, the observations of radio galaxies and quasars indicate that the universe is evolving. Further, the observed isotropy of the 2.7 K microwave background radiation,[74] its black body spectrum[75] and its high energy density have provided strong support to the Big Bang Model of the Universe. Also the observed abundance of light elements[76] and many detailed investigations at optical, infrared and X-ray bands[77] have provided us a wealth of new insights into the structure and evolution of the Universe. One of the most exciting recent developments is the discovery of superstructures, bubbles and voids in the distribution of galaxies.[1,2,78] Inspite of the rapid progress on the observational front, backed by a great deal of theoretical effort during the last decade, our present understanding of the formation of galaxies is still far from satisfactory and is marked with considerable uncertainty.[79]

Search for Protoclusters and the Giant Metrewave Radio Telescope

Before the era of formation of galaxies and clusters in the Universe, there are likely to have existed giant clouds of neutral hydrogen with masses exceeding 10^{13} $M_{\odot}$. Since quasars started forming at redshifts of about 4 or 5 and upper limits on the fluctuations in the intensity of the microwave background radiation of less than 1 in 10^4 indicate that the hydrogen clouds probably condensed not earlier than $Z \sim 20$, the frequency range of about 100 to 300MHz ($Z \sim 4$ to 15) seems most promising for making a deep search for the expected highly redshifted neutral hydrogen clouds.[80] This is one of the major objectives of the Giant Metrewave Radio Telescope (GMRT) to be set up by 1992 about 80km north of Pune.

GMRT will consist of 34 fully steerable, 45 meter diameter parabolic dishes (Fig. 13). Sixteen of these antennas are to be placed in a central array of about 1km × 1km is size and the remaining along the 3 arms of 14km in length each in a Y-shaped configuration (Fig. 14). A novel design has been developed for the 45m dishes. GMRT will operate at several frequency bands protected in the metre and decimetre region for radio astronomy, namely 38, 152, 325, 610 and 1420MHz. Observations are also planned at 232MHz.

Conclusions

Observations of radio galaxies and quasars have provided us with valuable clues about the evolutionary history of the Universe. Radio source counts and deep optical identifications have indicated that the strong evolution in the space density and/or luminosity function of radio galaxies may have taken place at earlier

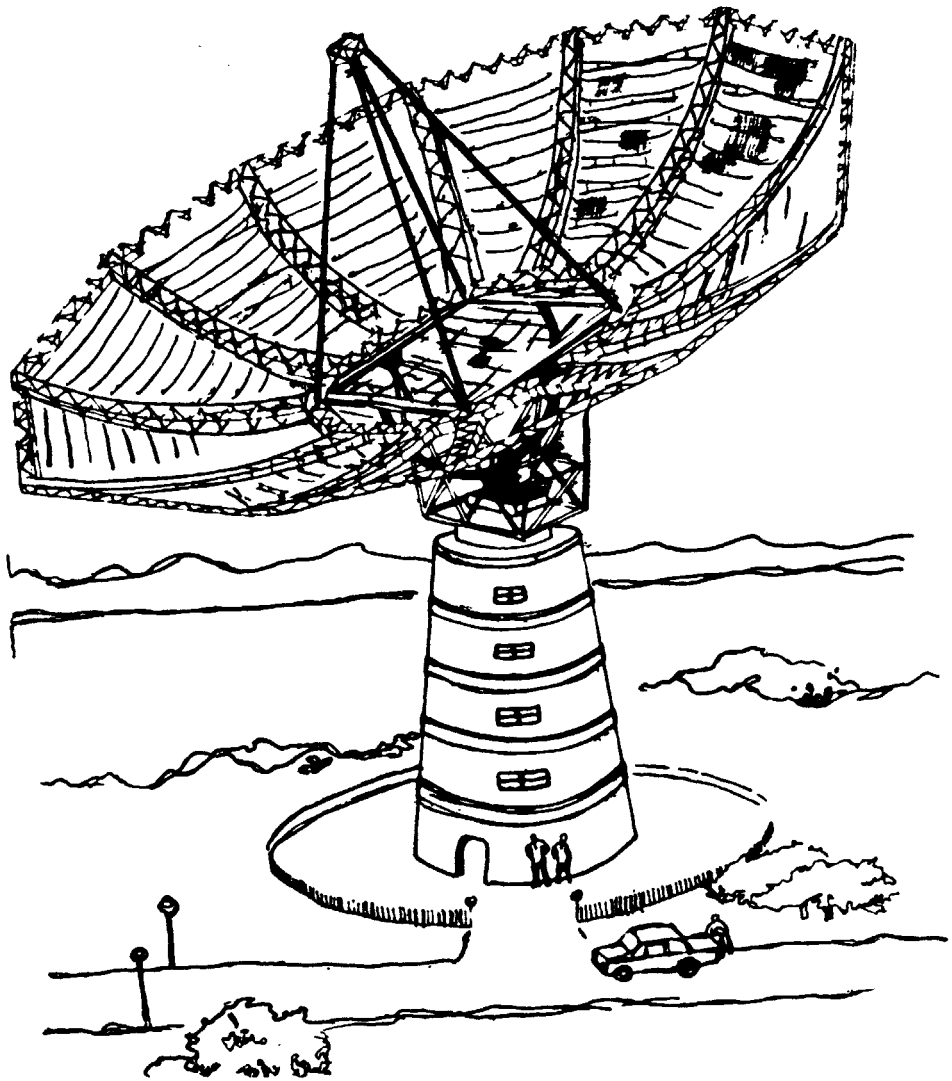

FIG 13 An artist's sketch of a 45m diameter parabolic dish of Giant Metre Wave Radio Telescope. The surface consists of 1cm × 1cm mesh made of stainless steel wire of 0.55mm diameter near the central part of the dish increasing to 2cm × 2cm near the outer parts. Rope trusses are used to achieve the curved reflecting surface of the dish. In the final design it is planned to use 16 frames instead of 12 shown in the figure.

cosmic epochs upto a redshift of ~ 3. The quasar evolution seems to continue at even higher redshifts but perhaps at a reduced rate. The observed decrease of linear size of radio sources with redshift can be explained either by considering a hot intergalactic medium or a higher pressure of haloes around active galaxies at earlier cosmic epochs.

Over the next few years, new measurement of microwave background may give us more positive clues about the scale and degree of anisotropy in the early

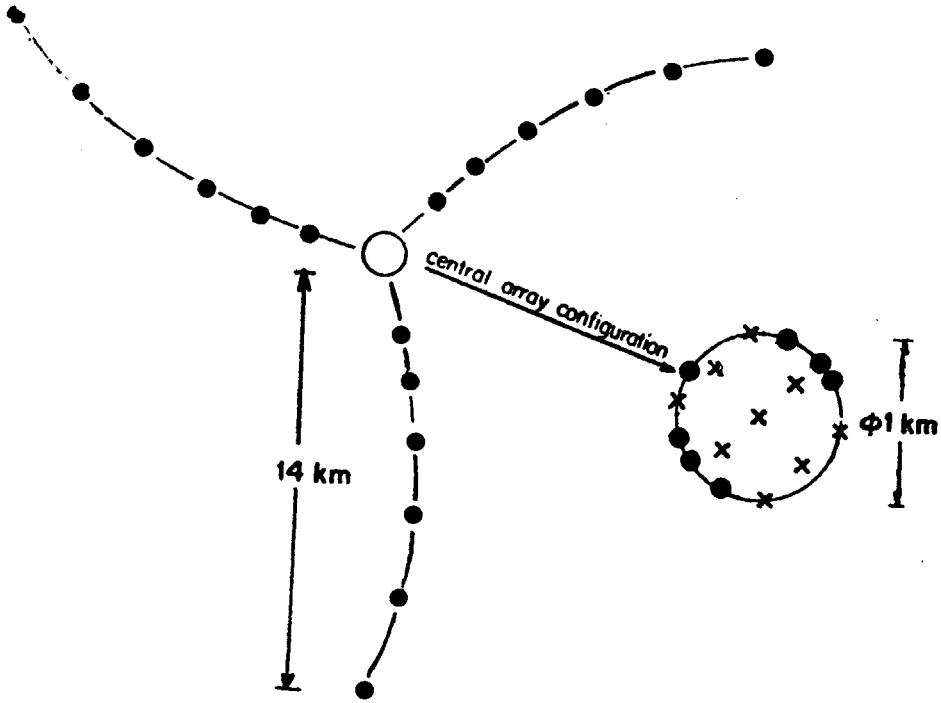

FIG 14 Array configuration of the Giant Metrewave Radio Telescope consisting of 34 Nos. of 45m diameter steerable dishes. A 3 × 3 grating configuration is to be placed near the central region, to allow pulsar search. The configuration is being optimized.

Universe. Other valuable inputs are expected to come from the search for proto-galaxies in the optical window and for the redshifted 21cm line radiation from the collapsing clouds of neutral hydrogen which presumably existed at Z between ~ 3 and 10. The latter will be one of the main objectives of the Giant Metrewave Radio Telescope.

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