The Presidential Address

DISTANCE INDICATORS IN RADIO ASTRONOMY

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INTRODUCTION :

Since no sharp characteristics have been observed in the radio spectrum of extragalactic radio sources, their distances can be estimated only by measuring the redshifts of their optical counterparts. Of about 20,000 radio sources catalogued so far, however, optical indentifications are available for less than 10 per cent sources. But redshifts have been determined only for a few hundred objects, most of which are QSOs. For the case of radio galaxies, it has been possible to measure redshifts only for the brighter galaxies. Thus there has been considerable bias in the selection of objects for which redshifts have been measured. Because of severe difficulties in observing the fainter objects, it seems unlikely that the situation will improve in the near future. Also, cosmological interpretation of redshifts is not certain. It would be of considerable value, therefore, if one could estimate distances of radio sources based on radio characteristics alone, even though on an approximate basis.

CORRELATION OF RADIO CHARACTERISTICS WITH REDSHIFT :

As is true in all branches of astronomy, a radio astronomer basically measures only the following parameters of radio sources : (a) flux density, (b) brightness distribution and angular size, (c) spectrum, (d) polarization and (e) variability. Many attempts have been made to investigate inter-correlation of these parameters and their dependence on redshifts (Bolton 1969, 1971; Fomalont 1969 ; Bash 1968 ; Kellermann 1972; Conway et al. 1974). We review here findings of these studies. Also, we present some new results on correlations between angular sizes of the components of double sources and redshift z. Our main aim is to investigate parameters which are more useful as distance indicators of radio sources.

Flux Density-Redshift Correlation :— The well-known log *N*-log *S* relation (number *vs* flux density) for extragalactic radio sources, investigated by Ryle and his colleagues (Ryle 1968 ; Pooley and Ryle 1968) indicates that there is an excess of weaker radio sources which are farther away. However, Hoyle and Burbidge (1970) have shown that there is a poor correlation between S and z, even for radio galaxies, and have suggested that S might not be a distance indicator. It has been pointed out by von Hoerner (1973) that a poor S-z correlation would be expected if the luminosity function of radio sources is 'flat' or 'critical', in which case sources in a given flux density range would have a wide distribution of redshift values. On the other hand, redshifts have been measured only for those radio sources which are associated with the brighter galaxies and are most probably nearby objects. Most of these sources have also large flux densities and angular sizes, as can be seen from Table 1 in which we present statistics of optical indentifications and redshift measurement for the complete 3CR sample of 197 sources within an area of 4.2 steradian of the sky (Longair and Gunn 1975). We present below some new results indicating that weaker sources are on the average located farther away than the stronger sources. Nevertheless, it can be shown that flux density is not a useful parameter as a distance indicator due to a broad width of the observed 'luminosity distribution' of radio sources.

Table 1

Statistics of optical indentifications and redshift measurements for 197 sources of 3CR complete sample

S_{408} (Jy)	$\theta > 60''$				$\theta < 60''$			
	U	*Q*	*G*	Total	*U*	*Q*	*G*	Total
<10	8	1 (1)	12 (8)	21	40	33 (26)	34 (8)	107
$\geq$ 10	1	1 (1)	31 (27)	33	7	12 (10)	17 (7)	36

U=unidentified ; *Q*=QSO ; *G*=Galaxy.

Numbers of sources for which redshifts have been found are given in brackets.

Angular Size-Redshift Correlation :—The correlation between angular size and redshift of radio galaxies and quasars has been studied by Legg (1970), Miley (1971) and Wardle and Miley (1974). It is found that there appears a well-defined upper envelope for the "largest angular size" (LAS) θ of radio sources plotted against redshifts. The individual data points show considerable scatter by a factor of about 10. The scatter is much more than would be expected due to projection effects and is perhaps due to intrinsic scatter in linear dimensions of the sources depending on their ages as well as initial conditions such as internal energy, momentum etc. The upper envelope of angular sizes decreases nearly as $1/z$. Since this result is in contrast to expectations for sources of constant linear size in Friedmann models, in which θ-Z relation exhibit a minimum, it has been concluded that the linear sizes of radio sources were smaller at earlier epochs. However, these results are primarily dependent on the cosmological interpretation of quasar redshifts.

It is interesting to enquire whether the sizes of individual components of radio sources, ω_{11} and $\omega_{\perp}$, in directions parallel and perpendicular to the major axes of the sources respectively, have less intrinsic scatter than θ. From high resolution observations made at Cambridge, Westerbork, Green Bank and Jodrell Bank for the 3CR sources, we have determined values of ω_{11},$\omega_{\perp}$, and θ for 62 out of 88 sources from the 3CR complete sample for which redshifts are known. This subset of 62 sources includes all double sources and those complex sources which show peaks at their outer edges similar to the double sources. It excludes single sources, core-halo sources, variable sources and compact sources with LAS $<$ 1 arc sec. A few sources with complicated structures are also excluded. An average value of the sizes of the outermost components was determined to give values for ω_{11} and $\omega_{\perp}$. For several sources, these estimates could be in error by factors upto 2, in view of inadequate resolution of observations. These values of ω_{11}, $\omega_{\perp}$ and θ are plotted in figure 1. The solid lines are drawn near the upper envelope of the data points with a slope of -1.0, which is the slope expected for a static Euclidean universe The broken lines are made lower by a factor of 10. It is seen from figure 1 that the degree of scatter is nearly the same for the 3 parameters. Although there exists some correlation between the parameters, i.e. sources with larger θ have also larger ω_{11} and $\omega_{\perp}$ values compared to their average values for a given z, there also exists a randomness so that a weighted average reduces the scatter by about 20 percent. Thus, it is found that the distances of most of the double or complex radio sources can be estimated from their angular sizes to within a factor of about $\sqrt{10}$ (r.m.s. value of the factor $\sim 10^{\frac{1}{4}} \sim 1.8$).

Angular Size -Flux Density Correlation :–Recently Swarup (1975) has made a comparison of largest angular sizes θ of a sample of 163 weak radio sources, studied at Ootacamund by the lunar occultation method, with those of 199 3CR sources. It is found that the median values of angular sizes increase with increasing flux densities (nearly as $\theta \propto S^{\frac{1}{2}}$) over a flux density range about 0.3 to 100 Jy at 408 MHz. There is an indication that θ_m reaches asymptotically a value of $\sim$ 8 sec arc as S decreases below about 1 Jy at 408 MHz. If a class of sources is uniformly distributed in space, we expect $\theta_m \propto S^{\frac{1}{2}}$ in Euclidean geometry. These results indicate that both θ and S are reasonable distance indicators. Kapahi (1975) has used this relation together with angular size counts to conclude that density and/or luminosity of radio sources was higher and linear size smaller at the earlier epochs of the universe.

Luminosity – Surface Brightness Correlation :— Heeschen (1966) showed a correlation between luminosity (Sz^2) and surface brightness (S/θ^2), which are intrinsic source properties, and suggested that this correlation could be used to estimate distances. However, we can get the same information from the θ-z correlation.

Correlation of Scintillation Visibility with Angular Extent and Flux Density :—Rapid scintillations are observed if the radio waves from a distant source pass through the interplanetary medium close to the Sun. These

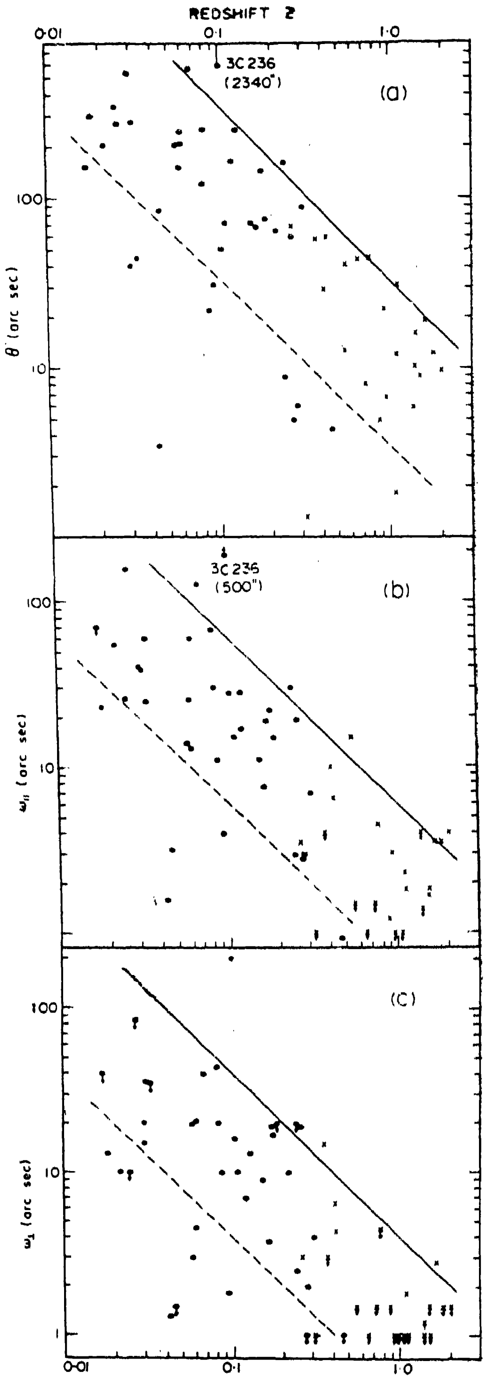

Fig. 1. Angular sizes θ, ω_{11} and $\omega_{\perp}$ of 62 sources are plotted against redshift z in figures (a), (b) and (c) respectively.

studies provided estimates of the fraction of flux density, μ, arising from compact components with size $\leq$ 1 arc sec. The correlations between (a) μ and S and (b) μ and θ have been studied recently by Swarup and Bhandari (1975). These correlations indicate that the weaker sources have smaller angular sizes, as would be expected if these are located farther away. It also seems that most sources have appreciable fraction of their flux density originating from compact components with size $\theta/10$ to $\theta/30$. A correlation between μ and z has been noted by Harris (1973) but shows a large scatter.

Spectral-Index and Redshift Correlation:—It has been shown that there exists a correlation between the spectral index α, and luminosity of those 'elliptical' radio galaxies which consist of two or more components but none of them lying at the position of the associated optical galaxy (Veron et al. 1972). Since the range of flux densities in the 3CR sample is small, the distribution of luminosities in the sample is determined mainly by the distribution of redshifts. Thus, there is also found a correlation between α and z. In figure 2 we have plotted α *vs.* z for the sample of 62 sources. There is a clear correlation but the values show a scatter by a factor of about 20 in the direction of z.

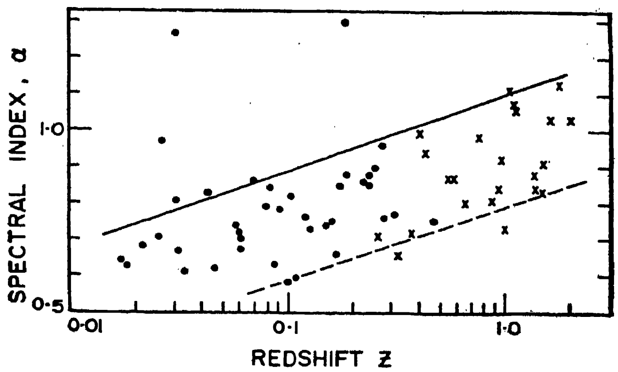

Fig. 2. A plot of spectral index α against redshift z

Polarization—Redshift Correlation:—It is well known that the radio emission from extragalactic radio sources is linearly polarized. The percentage of integrated polarization, m, is typically a few percent. It is maximum at centimetre wavelengths and decreases gradually as wavelength increases. For QSOs, the variation is often irregular. If we exclude these and also those with flat or concave spectra, it is found that the value of m at the emitted wavelength of 6 cm (wavelength at which observations are made being 6 $(1+z)$ cm) and depolarization at emitted wavelngth $\lambda_{\frac{1}{2}}$ at which m becomes 50 percent show a good correlation with z (Kronberg et al 1972; Morris and Tabara 1973; Vallee 1974; Conway et al. 1974). But the correlation with z becomes poor if m or $\lambda_{\frac{1}{2}}$ refers to the observed wavelengths rather than the emitted wavelengths. Therefore, these parameters provide only rough estimates of the distance of radio sources.

CONCLUSIONS:

From angular size data, it seems that distances can be estimated for radio sources with moderate flux densities which consist of two or more components but do not have flat or concave spectra. In most cases, the errors in the estimated distances are likely to be within a factor of about 3. Other radio parameters show a larger scatter with redshift than that for θ-z or ω-z correlations. However, all these parameters provide valuable information and make it possible to select a homogeneous sample of radio sources. Also, they can be used to predict statistical trends. For example, the θ_m— S relation found by Swarup (1975) indicates that the weaker sources have higher values of z, and therefore sources with $S_{408} \sim 1$ Jy should have higher values of α This has been observed by Grueff and Vigotti (1973) for Bologna sources. Also, since most of the weaker sources with high z would have high luminosities, we can expect that the orientation of the electric ploarization vectors should be perpendicular to their major axes, as is found for the sources of high luminosities in the 3CR sample.

The continuity between the observed properties of radio galaxies and QSOs has been used as an argument for the cosmological distances of QSOs. But many astronomers do not find this argument convincing as the observed dependences of the radio parameters on z do not agree with the predictions of world models, unless one introduces somewhat arbitrary changes with distance in the physical parameters of radio sources (Kellermann 1972). It is hoped that high resolution observations providing angular size, spectrum and polarization data for strong as well as weak radio sources would lead to better estimates of their distances from radio measurements alone. In any case we need many more measurements of redshifts and accurate optical magnitudes in order to investigate their correlations with radio parameters and also to understand evolution of radio sources of different types.

ACKNOWLEDGEMENT :

I wish to thank Mr. Gopal-Krishna and S. Anathakrishnan for help in the analysis and for valuable comments. I gratefully acknowledge the receipt of a Jawaharlal Nehru Fellowship during the course of this work.

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