# THE ANGULAR DIAMETER-REDSHIFT RELATION FOR SCINTILLATING RADIO SOURCES

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Observational evidence on the angular diameter-redshift relation using radio sources has, until recently, been confined to studies of the overall angular size. In this paper a different approach is described in which the very compact hot spots in radio sources are used as standard measuring rods. Such hot spots appear to be especially suitable for cosmological studies for the following reasons.

(a) Hot spots which contain one half or more of the total flux density are generally found only in the most powerful sources ($P_{178} \gtrsim 10^{27}$ W Hz$^{-1}$ sr$^{-1}$).

(b) Hot spots appear to show a smaller dispersion in physical size than the overall source dimensions.

Hot spots typically have steep radio spectra ($\alpha > 0.6$) and are found near the outer extremities of powerful double sources (Readhead & Hewish, 1976). They should not be confused with the central components of radio sources which have much flatter spectra and have angular diameters in the milliarcsec range.

The only powerful source which is near enough for the hot spots to be mapped in detail is Cygnus A. A small amount of data is available from intermediate baseline interferometry at low frequencies, but for information on a large sample we must, for the present, rely upon the technique of interplanetary scintillation which provides an angular resolution in the range 0.″1 - 2.″0.

In the method developed by Readhead and I the angular diameter is derived from observations of scintillation over a large range of solar elongation. Scintillation versus elongation curves of this type are found to exhibit good repeatability from year to year and the angular diameter is derived from the slope as measured between elongations of 35° - 90°. The method is believed to have random errors of about ± 0.″1 for strongly scintillating sources although there is a possibility of some systematic error due to uncertainties in the adopted model of the

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solar plasma. Cross-checking of scintillation and interferometric measurements at the same frequency should remove any systematic error. In the meantime the limited data available suggest that this error is not large.

The information provided by scintillation is roughly equivalent to that given by the fringe visiblity of an interferometer taken across the largest dimension of a scintillating component. If a source contains several hot spots within an overall diameter of $\lesssim 1''$, or if a hot spot lies within a halo of $< 1''.0$, an equivalent diameter of intermediate size is derived and the apparent flux density in the scintillating component is reduced. If several hot spots are separated by more than about 1" they scintillate almost independently and a mean diameter, strongly weighted towards the smallest component, is derived. A study of blending effects has shown that errors in the case of core-halo type sources only become serious when the halo has an angular diameter of $\lesssim 0''.5$ (Hewish & Readhead, 1976).

In a study of identified sources in the complete sample of extragalactic 3C sources away from the galactic plane a strong correlation has been found between the occurrence of hot spots and the overall linear size. The scintillation measurements were made at 81.5 MHz with the 4.5 acre telescope (Readhead & Hewish, 1974). These results show that hot spots which contain at least half of the total flux density are a common feature of powerful sources whose overall extent is less than 200 kpc, but are rarely found in sources with an overall size larger than 300 kpc. This is illustrated in Fig. 1.

The linear diameters of the hot spots themselves are scattered in the range 1 - 10 kpc and show no correlation with overall size. As shown in Fig. 2, however, there is evidence for an increase of size with increasing luminosity. A selection effect which acts against the detection of the larger hot spots in the weaker, and therefore nearer, sources certainly exists, but it is unimportant when the luminosity $P_{178}$ exceeds $10^{26}$ W $Hz^{-1}$ $sr^{-1}$. It should also be stressed that the upper limit of about 10 kpc for the hot spots cannot be explained by observational selection. There are only 8 sources in the sample classified as weak scintillators having $P_{178} > 10^{27}$ W $Hz^{-1}$ $sr^{-1}$. All of these have been observed with the 5 km telescope and in only one instance (3C 300) is there evidence for a hot spot having a diameter in the range 10 - 20 km. It follows that hot spots are a distinct feature of the most powerful sources and that there is not a continuous distribution of component sizes between hot spots and more extended features having sizes greater than 20 kpc.

To study the angular diameter-redshift relation requires the most accurate scintillation measurements and for this purpose a restricted sample was chosen for which the angular diameters are believed to be accurate to $\pm 0''.1$. All the sources in this sample contain at least 40% of their total flux density in hot spots. A few sources in this category having spectral indices of less than 0.6 were rejected to

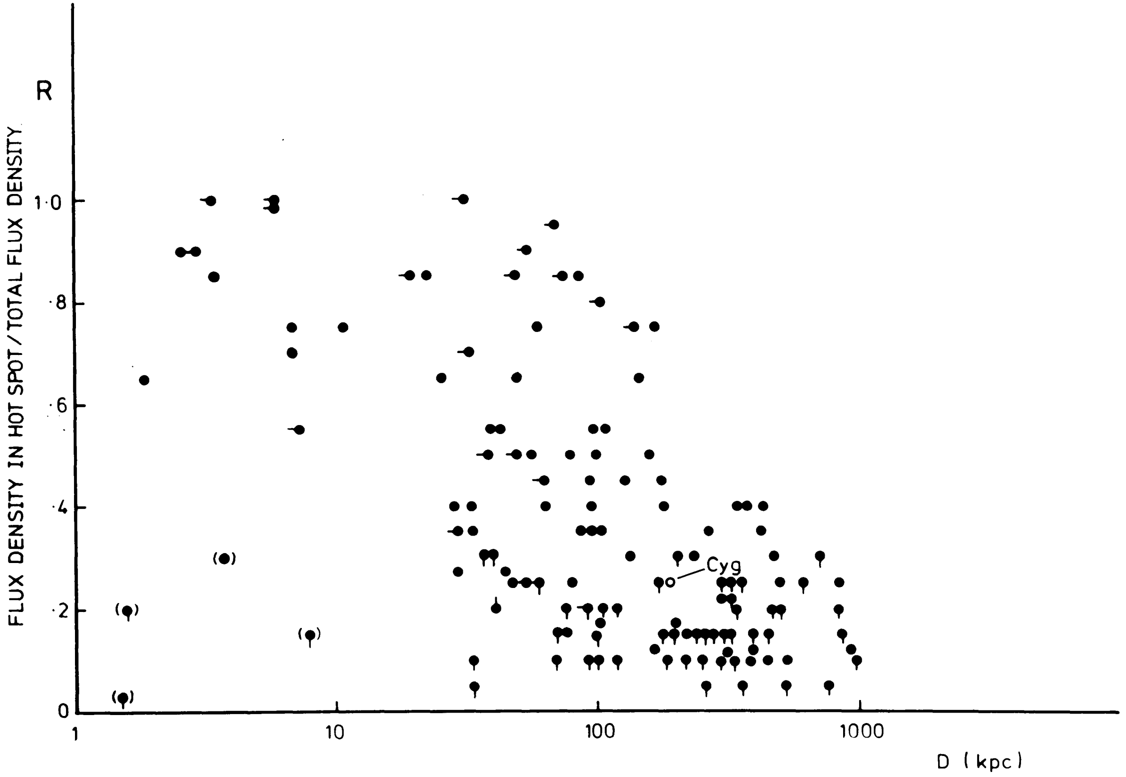


Fig. 1 The fraction of the flux density in hot spots versus overall physical size.

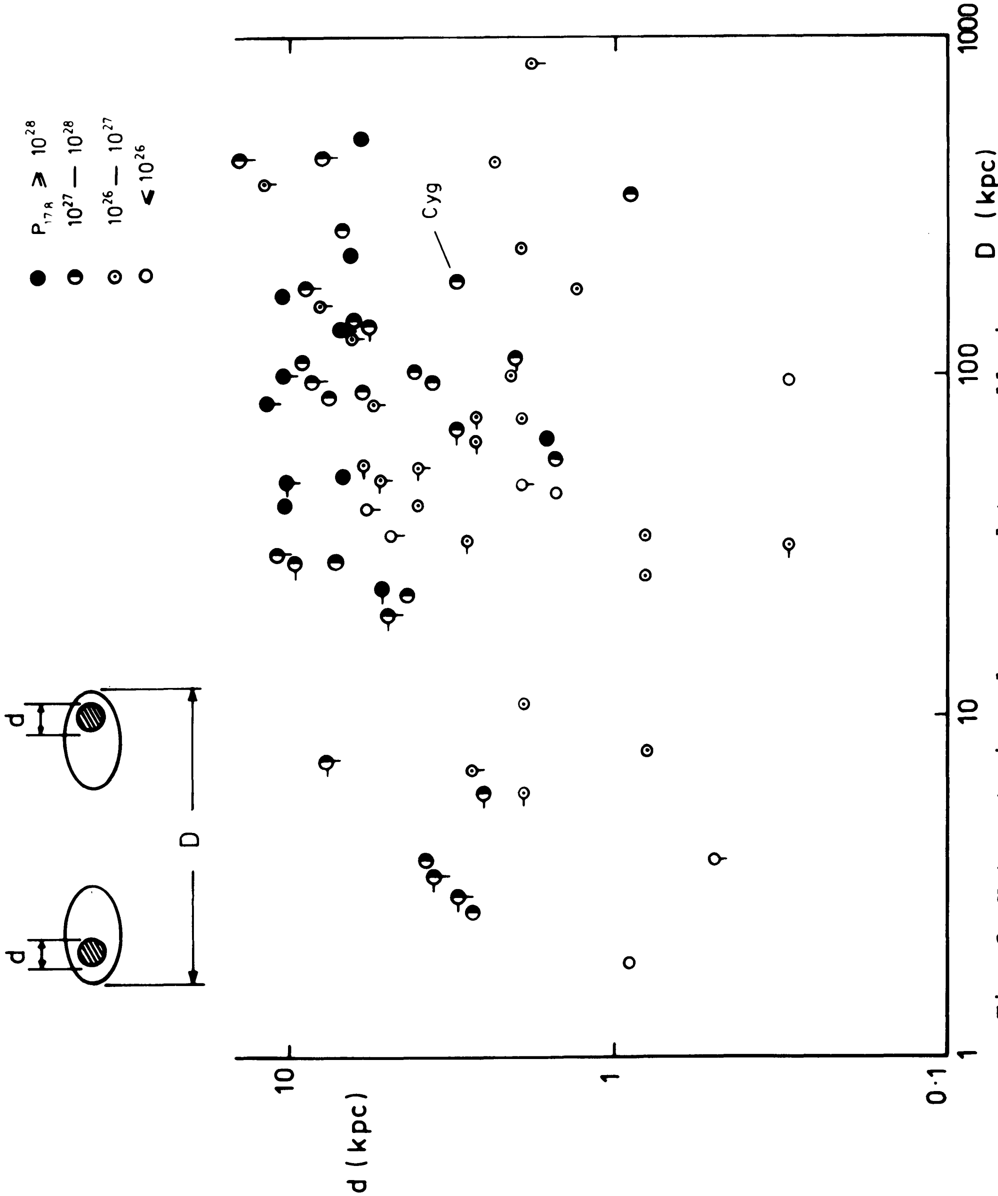


Fig. 2 Hot spot size, d, compared to overall size,

eliminate any possible contribution to scintillation from central components. The results are shown in Fig. 3.

The angular diameters are substantially independent of redshift in the range $0.2 < Z < 2.0$. The absence of sources near the lower resolution limit at large redshifts is particularly significant since the scintillation method is strongly weighted towards the detection of sources of the smallest angular size. These results cannot be seriously influenced by interstellar scattering since many of the sources have been studied at both 151 MHz and 81.5 MHz and the angular diameters do not scale as $(\text{frequency})^{-2}$.

The possibility of blending between hot spots and more extended features which also scintillate has been suggested by Swarup & Bhandari (1976) to account for the absence of small angular diameters at large redshifts. We have shown that this explanation would require a large fraction of the sources to contain hot spots of angular diameter $\lesssim 0.''2$ within more extended components of diameter $\sim 0.''5$ (Hewish & Readhead, 1976); another possibility would be that hot spots are clustered within an area of diameter $\sim 0.''5$. In the light of present evidence suggesting a low value for the deceleration parameter $q_o$, the simplest model appears to be that the hot spots actually are physically larger in sources which have large redshifts.

In conclusion, brief mention should be given to a new type of scintillation study being carried out by Duffett-Smith. The sensitivity of our radio telescope at 81.5 and 151 MHz should be adequate to detect a background level of scintillation due to sources of low flux density which are too numerous to be resolved individually. The method is essentially an extension of the statistical P(D) analysis introduced by Scheuer long ago. It is difficult to apply in practice since great care is needed to eliminate spurious effects which might arise from, for example, ionospheric scintillation or terrestrial interference. Weather balloons over the continent are already causing difficulties. One result which can be stated now is that the maximum scintillating flux density at an elongation of $15^o$ does not exceed $0.23 \pm 0.03$ Jy at 151 MHz. This value is appreciably lower than would be expected if the background sources contained similar hot spots to the 3C sample. The hot spots in these weak sources must either have a larger angular size, or contain a smaller fraction of the total flux density, than the stronger sources. The cosmological implications of these conclusions will depend, of course, upon the intrinsic luminosity of the sources. If the sources have comparable luminosities to the 3C sample, but are at larger redshifts, the result could indicate an increasing trend for hot spots to have large angular size at large redshifts.

## References

Hewish, A. & Readhead, A.C.S., 1976, Astrophysl Letters (in press)
Readhead, A.C.S., & Hewish, A., 1976, Mon.Not.R.astr.Soc.(in press)
Swarup, G. & Bhandari, S.M., 1976, Astrophys. Letters, 17, 31.

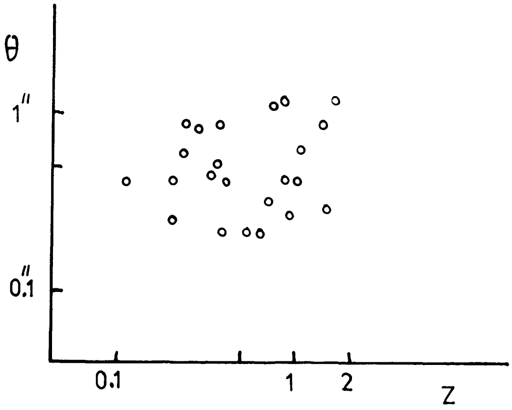


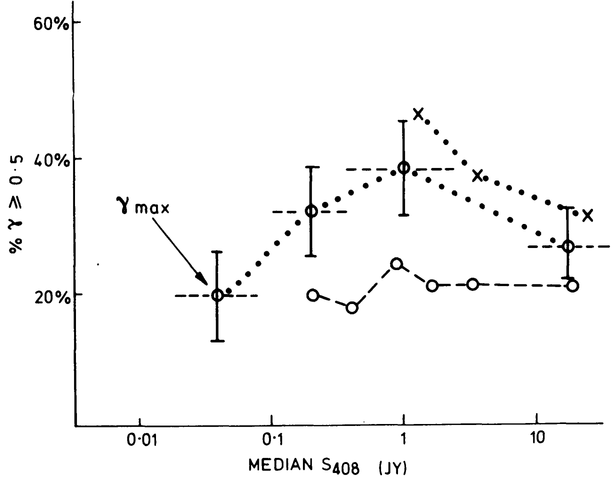
Fig. 3 The θ-z relation for hot spots in strongly scintillating sources.

## DISCUSSION

### THE S - θ RELATION AT 408 MHz

H.P. Palmer

Radio linked interferometers have been used at 408 MHz to investigate this relation. (Baselines 24 and 127 Km, $\gamma_{2.7} > 0.5$ if $\theta < 2.7''$ and $\gamma_{127} > 0.5$ if $\theta < 0.57''$). Anderson and Richards made drift observations at constant hour-angle in the Dec. 30° (Bologna) area, and found that the fraction of sources having $\gamma_T > 0.5$ increases from 29% to 41% between S = 14 Jy and S = 3 Jy for the 24 Km baseline. However the fraction remains approximately constant at 20% ± 4 for the same source observed with the 127 Km baseline. There are approximately 200 sources per point for the drift observations on figure 1.



Speed, Spencer and Warwick have made tracking observations at 408 MHz using the 127 Km baseline. They found that the maximum value of $\gamma$ observed on each track was the best indicator of the size of source components. The fraction of sources having $\gamma_{max} > 0.5$ was found to increase from 21% at $S_{medium} = 14$ Jy to 38% at 1 Jy and then to fall again to 20% by 80 mJy (for observations in the 5C2 and 5C3 areas). When the scintillation data of Readhead, A.C.S. and Hewish, A., Mem. R. Astr. Soc., 78, 1-49, (1974) and Swarup, G. and Bhandari, S.M., Ap. Letters, 18, 31, (1976) is expressed in the same form, it shows reasonable agreement on the rise between 14 and 3 Jy.

Speed has shown that these observations can be predicted from the properties of a complete sample of 57 3CR sources, considered to be moved to progressively larger redshifts, only if a density evolution index $\beta \simeq 6$ is assumed.

*Scheuer:* Prof. Hewish and Dr. Palmer have both made measurements of the sizes of components (as opposed to LAS). Would either of them care to say whether their results agree or disagree?

*Palmer:* A source by source plot of 45 sources showing $R_{scint}$ vs $\gamma_{Def\ 408}$ shows good correlation along a 45° line. However the scintillation data do not show a clear variation of R with flux. Both techniques show that R or $\gamma_{T\ Def\ 408} \geqslant 0.5$ for 20% ± 5 for sources with $S \simeq 1$ Jy at 408 MHz.

Concerning the components smaller than 0.2 arcsec absent from the scintillation data at 81 and 151 MHz, this interferometer data does not yet extend smaller than 0.3 arcsecs. Components showing partial resolution on this scale are seen at 1660 MHz, and by VLBI at lower frequencies.

*Hewish:* I do not see any inconsistency until the intrinsic luminosities of the sources have been measured. Our data indicate a significant decrease in linear size of hot spots with decreasing absolute luminosity and this might explain your correlation with flux density at 327 MHz. The interferometric data do not yet indicate that a large fraction of the high luminosity sources are less than 0.3 arcsec. It will be interesting to see what results are obtained from low frequency interferometry at higher resolution.

*Swarup:* According to Dr. Hewish, most of high luminosity radio sources have compact components with size at 81 MHz $\gtrsim 0.3$ arc sec. But, according to the Jodrell Bank observations presented by Dr. Palmer, the angular size of compact components decreases with flux density up to $\sim 1$ Jy at 408 MHz and these refer to sources of high luminosities at redshifts beyond about one, according to our present understanding. Decrease of angular sizes of the scintillating components with decreasing flux density is also indicated by scintillation measurements at 327 and 408 MHz, e.g. of half of the sources around 2 Jy at 327 and 408 MHz have visibility greater than 0.4, indicating that their sizes should be appreciably less than 0.3 arc sec. Thus there seems to be some inconsistency in the observations at 81 MHz when compared to those at the higher frequencies.

*Webster:* Could not the lack of small scintillation size at large redshifts also be explained by taking a more realistic source model?

*Hewish:* One model which could explain this result would be if the bulk of the large redshift sources actually consists of one or more hot spots of size $0''.1$ superimposed upon a halo of size about $0''.5$. So far there seems to be little evidence for the existence of steep spectrum sources having sizes as small as $0''.1$.

## ON THE INTERPRETATION OF ($\theta$ - z) Data

R.C. Roeder

Dyer and I have investigated effects which occur when a source of radiation at a large distance in a universe with mean density $\rho_u$, on some sufficient scale, is examined by a line of sight along which the average density, $<\rho>$, differs from $\rho_u$. (Dyer, C.C. and Roeder, R.C., Ap. J. (Lett), 1972, **174**, L115; 1973, **180**, L31; 1974, Ap. J., **189**, 167.) If we define $\alpha = <\rho>/\rho_u$, and select lines of sight which pass sufficiently far from intervening galaxies that we can ignore the shear (Weyl focussing) introduced by them, we need only consider any Ricci focussing ($\alpha > 1$), on each of it ($\alpha < 1$), relative to the usual homogeneous models ($\alpha = 1$).

If $\alpha < 1$, angular diameters at a given z will in general be smaller than those given by the usual ($\theta$-z) relations for homogeneous models. In the limit $\alpha = 0$, $\theta(z)$ is given by

$$\theta^{-1} \propto \int_0^z (1 + x)^{-3} \; (1 + 2q_o x)^{-\frac{1}{2}} \, dx,$$

where $q_o$ is the cosmological acceleration factor, assuming that Weyl focussing can be neglected. In order to evaluate situations in which shearing cannot be neglected, numerical integrations must be done.

Thus one cannot properly interpret ($\theta$-z) data without knowing something about the small scale structure of the universe.

*de Felice:* Would the determination of a minimum in the observed $\theta$-z relation give a direct indication of the degree of anisotropy along the line of sight?

*Roeder:* It is believed that the parameter $\alpha$ is nearly zero. In order to distinguish the shearing effect (Weyl focussing) from Ricci focussing, you have to be able to resolve sources. If there were no Ricci focussing ($\alpha = 0$), then a minimum in ($\theta$-z) would provide information about the anisotropy.

*Oort:* Have you made an estimate of how large $\alpha$ would be on the basis of what we know concerning the distribution of galaxies, assuming that the distribution of intergalactic matter is the same as that of the galaxies?

*Roeder:* I have not done so myself, but it has been suggested to me by various people that $\alpha < \frac{1}{2}$. However, the apparent detection of an intervening galaxy in the direction of 3C286 suggests that $\alpha$ will vary from one line of sight to another.

*Narlikar:* When $\alpha \to 0$, the minimum occurs at $z \to \infty$. Is it a finite minimum or a zero minimum?

*Roeder:* Finite, very similar to the case for $q_o = 0$.