US/GR 8k/

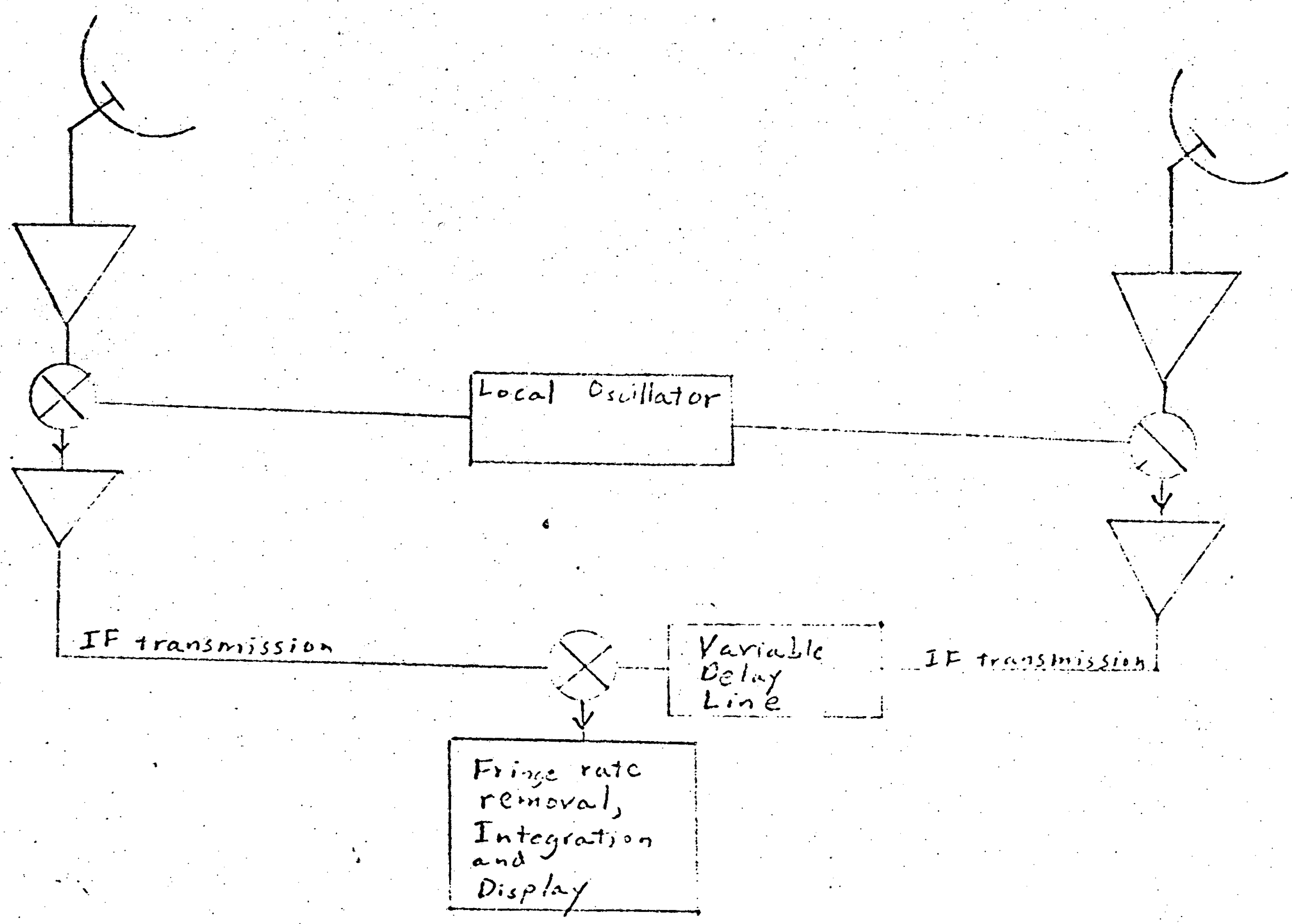
The Tape Recorder Interferometer and Small Diameter Radio Sources

Lecture Notes, 1970

B. Clark

I. The Tape Recorder Interferometer Technique

The tape recorder interferometer is in essence no different from more conventional ones. The over-all block diagram of almost any radio astronomy interferometer is given below.



In this diagram the X'ed circles represent mixers or multipliers -- basically the same process, as both involve multiplying the two inputs and rejecting the high frequency components of the output -- and the triangles denote amplifiers.

The same diagram can be used to discuss tape recorder interferometers with very little modification. The first modification is in the area of the local oscillator, which translates the radio frequency radiation from the radio source down to a more convenient frequency range. As drawn above, the same sinusoidal voltage from a common oscillator is used at the two ends of the baseline. In the tape recorder interferometer, sinusoidal voltages are generated at each end of the interferometer by separate oscillators governed by very good frequency standards. These frequency standards are sufficiently good that for the duration of the observation, essentially identical voltages are being generated at each end of the baseline.

The IF transmission lines in the drawing above are replaced by tape recorder systems. The IF signal is recorded at each end of the baseline, and the tapes are transported to some common location. The two signals are then reproduced in synchronism and are then processed by the remaining parts of the system.

II. Applications of the Technique

A. Orders of Magnitude of Relevant Quantities

Maximum Baseline $= 2\ r_\oplus = 12756$ Km

Maximum Geometric Delay $= r_\oplus/c = 21.3$ ms

For operation with a baseline of $r_\oplus$ and at frequency F (in GHz)

Baseline in wavelengths $= 21.3 \times F \times 10^6$

Fringe Spacing (seconds of arc) $= .0097/F$

Maximum Fringe rate (Hz) $= 1840 \times F$.

Tape recorder interferometers have been used at frequencies between 24 MHz and 23 GHz.

B. Jupiter Bursts

The high intensity rapid bursts emitted by the planet Jupiter at frequencies between 5 and 30 MHz have been measured to arise in regions less than 1" in size; that is, less than 4000 Km. The radiation is interpreted as arising from cyclotron or stimulated cyclotron emission from electrons energized by local "dumping" of the Jupiter van Allen belts. (See Dulk, 1970, Ap. J. **159**, 671).

C. Interstellar Masers

For a coherent radio source, such as the line emission masers due to inverted state populations in interstellar OH and H_2O clouds, the interferometer measures an intermediate value between the size of the region and the size over which spacial coherence is maintained. The OH maser emission sources have apparent angular sizes of 0.05 to 0.005 seconds of arc, corresponding to a few astronomical units at the source. However, it is suggested that these sources may actually be much smaller regions, whose radiation is spread by small angle scattering from interstellar electron inhomogeneities. The H_2O masers, at a much higher frequency, and hence much less affected by interstellar scattering, have limits on apparent physical sizes as small as 0.1 A.U., smaller than many types of stars.

D. The Synchrotron Sources

Synchrotron radiation is, in the rest frame of the electron, simply cyclotron radiation, or magnetic bremstrahlung, caused by the acceleration of the electron by the magnetic field. The Loren z transformation causes this radiation to be emitted in a cone of opening angle $\sim \frac{1}{\gamma} = \sqrt{1-\beta^2}$. An electron is accelerated through this angle in a time $\frac{2\pi m_e}{eB}\gamma^2$ so that no radiation of a single synchrotron electron consists of pulses of this duration. These pulses have spectral components up to a critical frequency

$$f_c = \frac{3}{2}\frac{eB}{2\pi m_e}\gamma . \tag{1}$$

Because there are many more low energy electrons than high energy ones, selecting the observing frequency effectively selects the energy of the electrons being observed.

The total power emitted by one electron may also be calculated as the blue shifted cyclotron radiation

$$P = \frac{\mu_o e^2 c}{6\pi}\frac{e^2 B^2}{m_e}\gamma^2 . \tag{2}$$

Observing at frequencies where the emitted power is a maximum, we may insert the observed power emission in equation 2 to derive a relation between the total number of electrons, the field B, and the energy γ.

By thermodynamic arguments, the emitted brightness temperature cannot exceed the equivalent electron kinetic temperature, i.e. at frequencies where the source is optically thick

$$T_b \sim k\gamma m_e c^2 \tag{3}$$

If one measures the brightness temperature of the sources, then these three relations allow one to solve for the three quantities -- the total number of electrons, the magnetic field, and the energy of the electrons emitting at a specific frequency.

A more exact treatment, taking account of the non-thermal nature of the electron energy distribution, and of the various pitch angles between the electrons and the magnetic field, yields the relation

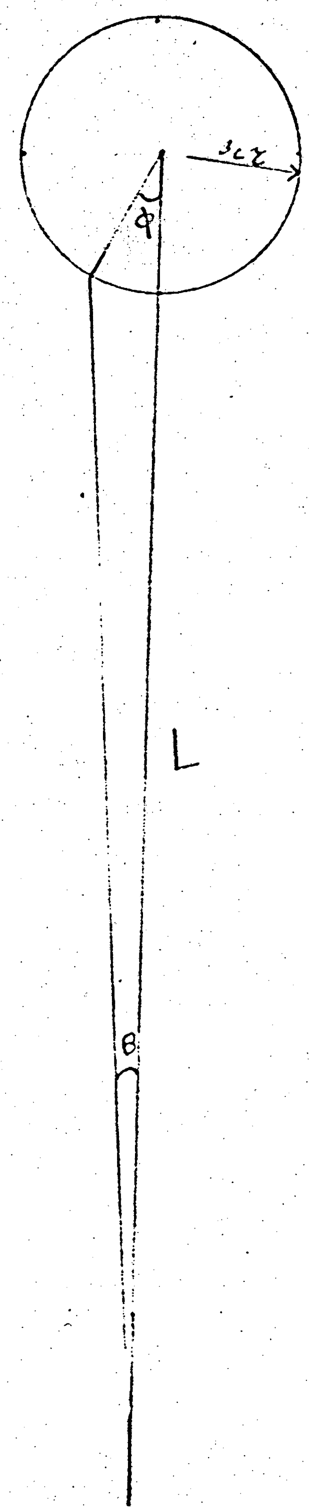
$$B = 2.44 \times 10^{-8} \, \theta^4 \, S_m^{-2} \, \nu_m^5 \, (1 + z)^{-1}$$

for the magnetic field, B in gauss, θ the angular size in seconds of arc, ν_m the frequency of peak emission in megahertz, and z the source redshift. This equation gives a direct measurement of the magnetic field in a synchrotron emission source. (See Clark, et al., 1968, Ap. J., 153, 705).

E. The Variable Synchrotron Sources

Consider a source expanding with speed βc, starting at $t = o$. At time t it will be a shell of size βct. Radiation emitted at angle ϕ will arrive at the earth at epoch

$$T = t + \frac{L - \beta ct \cos\phi}{c}$$



and it will appear to come from an angle θ removed from the center,

$$\theta \approx \frac{\beta ct \sin\phi}{L}$$

The radiation arriving at a given epoch T thus arrives at angles θ

$$\theta = \frac{\beta c}{L}\left(T - \frac{L}{c}\right)\frac{\sin\phi}{1 - \beta\cos\phi}$$

The maximum value of θ occurs for some ϕ_o, which satisfies

$$\cos\phi_o = \beta$$

and has a maximum value

$$\theta_o = \frac{\beta c}{L}\left(T - \frac{L}{c}\right)\frac{1}{\sqrt{1 - \beta^2}}$$

Thus, the apparent expansion rate for $\beta \approx 1$ is higher than c by the factor $1/\sqrt{1-\beta}$.

(See Gubbay et al. 1969, Nature, 224, 1094.)

3 us/GRBK/

Structure of Extragalactic Radio Sources.

W.B. McAdam
7/7/70

Early radio observations showed that many sources were extragalactic, and like the optical galaxies, required special instruments to explore their nature.

In the 3C catalogue (Edge et al. 1959) of 471 sources, information on size was obtained for 19 only, with upper limits for a further 49 sources. Aerials of at least 1000 λ were needed: interferometers, cross and T arrays, synthesis arrays and VLBI s are all the result of this search for resolution to examine the structure and evolution of radio sources.

Some Instruments.

Comparison of the Resolutions of some Observatories

Observatory	Method	Frequency (MHz)	Baselines (λ)	Reference
Molonglo	pencil beam	408	0–1065	Mills *et al.*[7]
	fan beams	408	0–2130	
Parkes	interferometer	468	190–665	Wall *et al.*[8]
		1401	570–2000	
Culgoora	pencil beam	80	0–800	Morimoto and Lockhart[6]
Cambridge	synthesis	408	0–2040	Macdonald *et al.*[3]
		1407	0–7050	
Owen's Valley	interferometer	1425	0–2300 EW	Maltby and Moffet[1]

Extensive observations have now shown that the size of extragalactic sources can range from 10° down to 6" with VLBI structure to .001". When combined with optical red shifts, the physical size is from 400 to 0.5 kpc and component size down to 3 light months (Virgo A)

Size overall	6.3	10	16	25	40	63	100	160	250	400	630	1000 "arc
						1	1.6	2.5	4	6.3	10	16 'arc
3C survey measured							4	7	6	1	1	
upper limits							11<	30<	8<			
M.K.N synthesis		1<	4	11	22	17	11	6	4	2	1	3>
Ekers interferometer					73<	12	7	10	11	12	1	(56 of 123)
Hogg partial synthesis 10<	6	7	5	1	1	2						(32 QSOs)
Miley 33<	4	7	5	4	5	4	5	.	.	1		(78 QSOs)

The QSO and galaxy identifications overlap in size and it is becoming harder to distinguish these as classes on either radio or optical data. Nearly all the big radio sources contain small unresolved cores, often at the centre of the optical galaxy. Three types, N, seyfert galaxies, and QSS seem to merge in optical characteristics. At large distances, only the cores of galaxies can be seen. These may occur in clusters, linked optically, and giving a radio halo (Arp 1970)

Optical magnitude	<13	14	15	16	17	18	19	20	unidentified	obscured
M.K.N. list	8	6	8	6	6	9	12	5	20	4
mean flux at 408Mhz (all sources 10.6±0.4)				9.4 ±1.4			8.8 ±1.5		7.6 ±0.9	

There seems to be no significant correlation between Radio flux and optical magnitude. The best correlation seems to exist between the maximum angular size and the red shift. This is shown for radio galaxies; it continues for QSOs with the most recent data from interferometers and synthesis arrays.

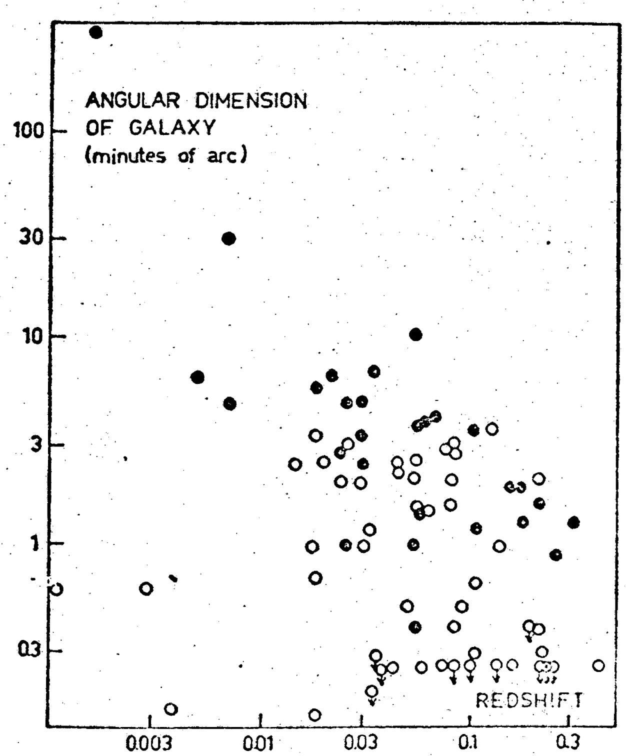


FIG. 2. Angular diameter-redshift diagram for the radio galaxies: Filled circles give the separation between components of double sources where the brightness distribution is known in detail.

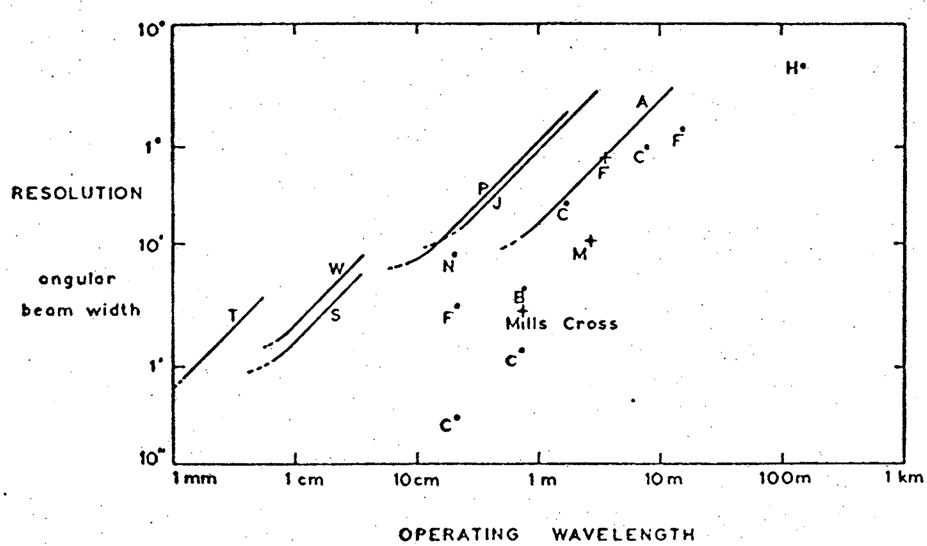
A corollary is that the luminosity of radio sources varies greatly.

From MKN. the distances vary from 3 to 2300 Mpc

the luminosity at 1407 MHz varies from 0.01 to 4600 w $Hz^{-1} ster^{-1} \times 10^{23}$

the minimum energy in the source varies from 0.003 to 1900 $\times 10^{57}$ ergs

Resolution of some major aerials.(operating 1966)



KEY

M—Molonglo—the Mills Cross.
F—Fleurs, Sydney—includes the first Mills Cross.
H—Hobart.
P—Parkes.
A—Arecibo—Puerto Rico.
B—Bologna—Italy.
C—Cambridge—England.
J—Jodrell Bank—England.
N—Nancay—France.
S—Serpukhov—USSR.
W—Washington—USA.
T—200 inch Palomar telescope—USA.

Structure of Three major Sources - Fornax, Virgo, Centaurus.

M.J. Cameron (1969)

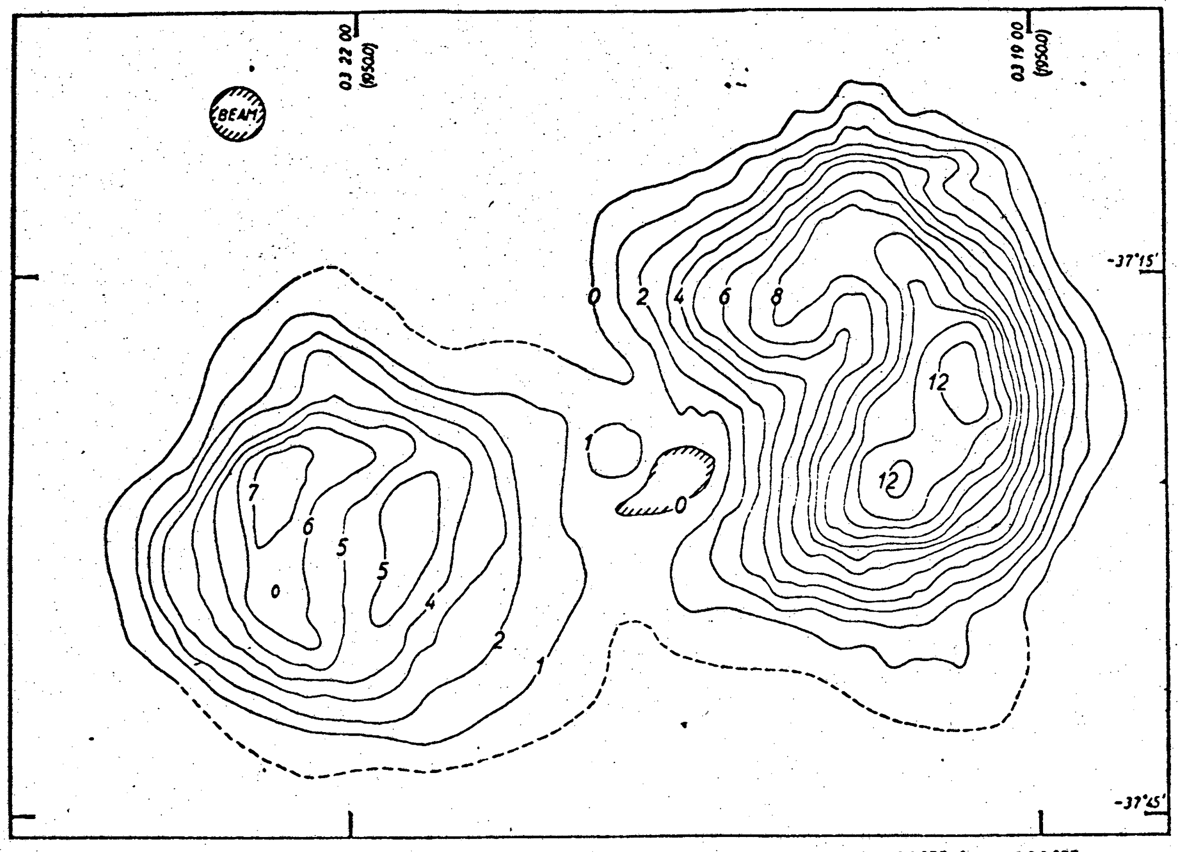


Figure 1. NGC 1316 (Fornax A). Contours of NGC 1316 at contour unit 100°K from 100°K.

10^m So galaxy, diam 4'.0; at 408 MHz 40' between ridges with central source 0.5 fu. unresolved. Spiral arms seem to link with arcs.

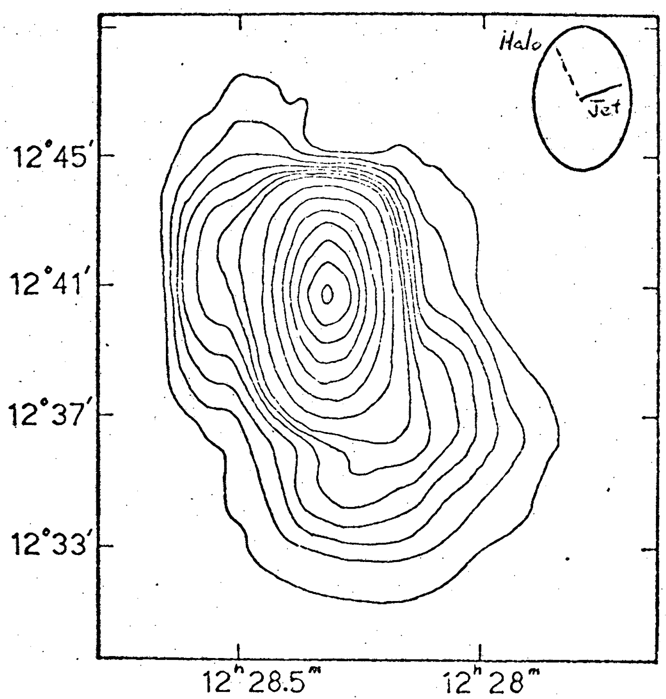


Figure 2. NGC 4486 (Virgo A) M87. Contour unit 1400°K from 1000°K to 9400°K and 6900°K from 14000°K.

$9^m.7$ E galaxy with jet in core, 13"arc. Halo 16' x 12' at 34° PA. Core has fine structure to < 0".002

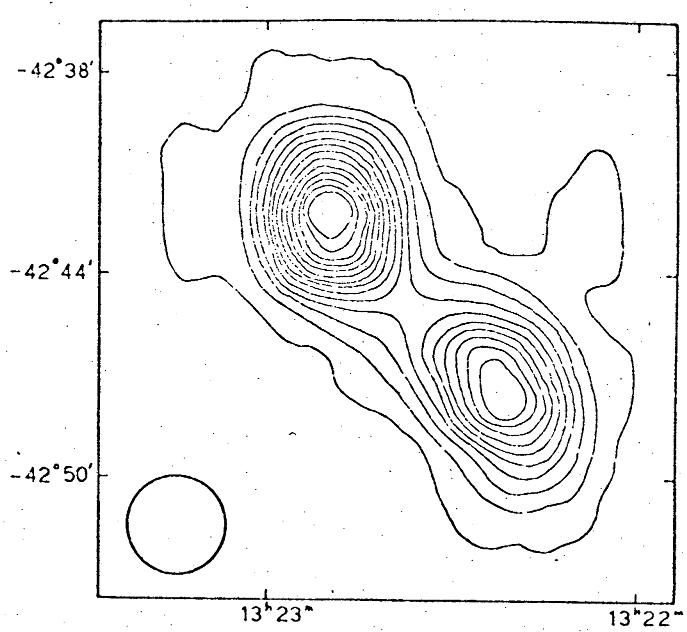


Figure 3. Central component of Centaurus A (NGC 5128). Contour unit 1650°K from 800°K.

Outer double source 5°.5 x 10°
Central double is 7'.1 sepn. at 46°.5 with bridge.

Morphology: either mapped (pencilbeam or synthesis) or model (interferometer).

	Partially resolved	Single peak	Halo	Double	Bridge double		Multiple or Complex
M.K.N. (S) 82 sources		12		25	19	D with complex comp. 20	6
Ekers (I) 56 sources	11	3	6	22	6		8
Fomalont (I + S) 80 sources		5	16	27		unequal D 10	22
Molonglo (P) 128 sources	point or confused 23	30		40	19	complex D 10	6
Hogg (S)	all those resolved were double			19			
Miley (S)			6	27			7

Random Doubles. The prevalence of doubles and the difficulty of identifying many of these suggestes that some may not be physically related. We take the distribution of sources (logN/logS) and calculate the random chance of having a pair with flux > S when the components have $S_1 + S_2 = S$ and ratio $S_1/S_2 < 10$.

At 408 MHz, for S = 5fu there would be random pairs within 10'arc of 36 in each hemisphere. We can limit the random number considerably if we demand that the individual components also be extended or resolved.

In Parkes catalogue, out of 1736 sources, 157 were listed as Ext. or Poss.Ext.

M.K.N. resolved 82 out of the 470 in 3C catalogue

Wall et al found 98 resolved out of 275 with S > 1fu at 11 cm.

McAdam finds about 35% sources extended and 9% resolved on both axes at 408.

The combinations of Resolved, Extended and Point components will occur by random

(in one hemisphere, $S_{408} > 5$fu spacing < 10')	RR	RE	EE :	RP	EP	PP
	0.3	1.7	2.5	4.2	12.2	15.1
		4.5			31.5	

Chance Identifications.

Wyndham gives the chance of galaxies <20^m lying within a square of 0.4' as 5%. We see later that the search square is not determined by the accuracy of the radio position, but by the possible separation between radio centroid and the optical object. This may reach 1 to 2'arc.

The mean spacing of 18^m galaxies is 8' so that the chance of being within 2' of a radio centroid is 25%; of being within 1' is 6%.

The most likely types are E,N,galaxies and these make up only 18% of all types.

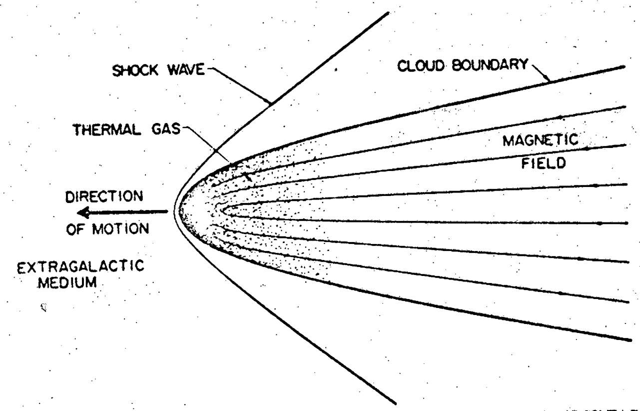
The mean density of stars <18^m is about 12000/°sq but only 10% of these are O,B types likely to be mistaken for QSOs. However this means that on survey plates there will be about 1 O or B star within 1' of any position <18^m.

The problem is easier at high galactic latitudes, since the density of stars is lower by 20 times at b = 90°.

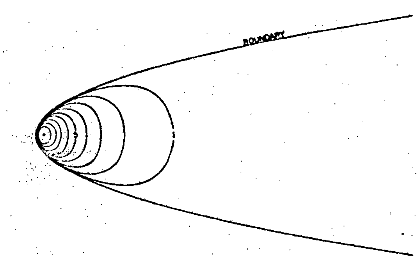
Source Mechanism.

Ryle and Longair (1967) have suggested a model for double sources in which two clouds of plasma are ejected in opposite directions from the galaxy. Since the speeds approach that of light, the two components will, in general, be observed at different ages and different angular separations from the galaxy. It is then possible to derive the luminosity and age for each component.

Mills and Sturrock (1970) have another model in which the galaxy forms from matter gathered at a reversal sheet in the intergalactic magnetic field. Gravitational energy is stored in the distorted field as the galaxy contracts (S to E type) until a flare ejects plasma at speeds $< 0.3\,c$.

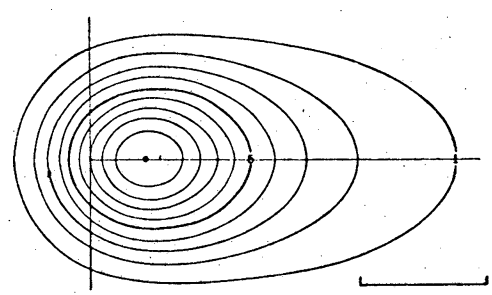


For both models, the most reasonable method of confining the plasma is by ram pressure of the intergalactic medium. Calculations give a profile to the component similar to the magnetosphere of the earth, and when observed with a finite beam-width, the peak is displaced from the centroid in the direction of motion away from the galaxy.



Alternate calculations by De Young and Axford (1967) give radio contours extended perpendicular to the motion.

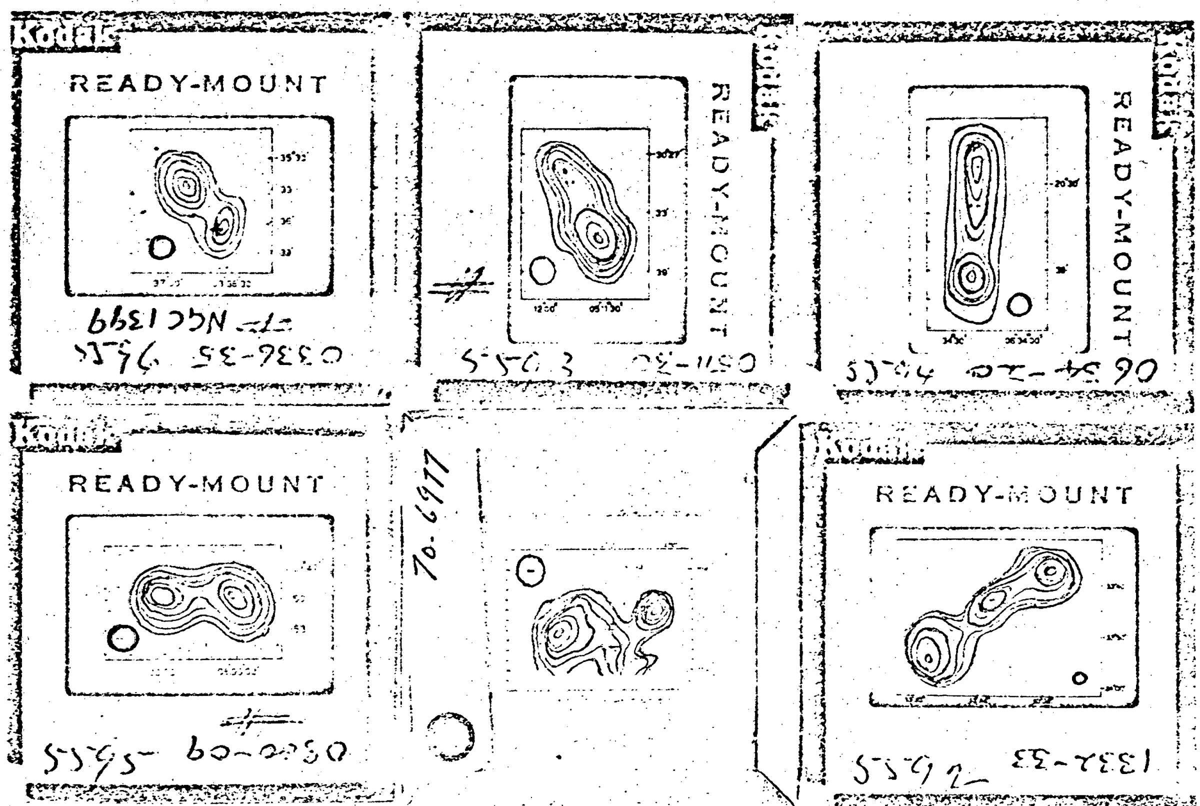
Both types have been seen (Cygnus A; Fornax A) but the Sturrock elongation is more common.



Further ejections may occur on the opposite side or along an earlier path, giving rise to the multiple sources found. However, the models do not describe diffuse or halo sources.

Some Sources with Extended Structure.

R.T. Schilizzi, W.B. McAdam (1970)



These brief slide copies are for a reminder only.

0336-35 NGC 13 99 $10^m.9$ E_0 ; double 5'.6 sep. at 36°. The minor peak is 45" from galaxy; centroid is 4'.6 at 35° from galaxy.

0511-30 ; double with strong bridge 7'.7 sep. at 26°, polarized. 17^m galaxy near bridge is a possible identification.

0634-20 elongated with 11'.5 between peaks at 179°. A $16^m.8$ E galaxy lies 4' south of the N. peak.

0800-09 ; 6'.8 sep. at 91° with components not aligned along axis. Many interesting optical objects; none confirmed.

1333-33 IC 4296 $11^m.9$ E ; triple spaced 12'.7 and 17'.7 with strong bridge between north pair. For distance ~ 24 Mpc size is ~ 240 kpc. Thought to be similar to Centaurus A. Strong polarization along the axis as shown below (11 cm Parkes: Gardner et al)

1400-33 NGC 5419 $12^m.4$ E;
9'.7 sep. at 99°; major comp. is 5' x 6'; centroid is 5'.0 from optical, which is ~40" from the smaller radio component.

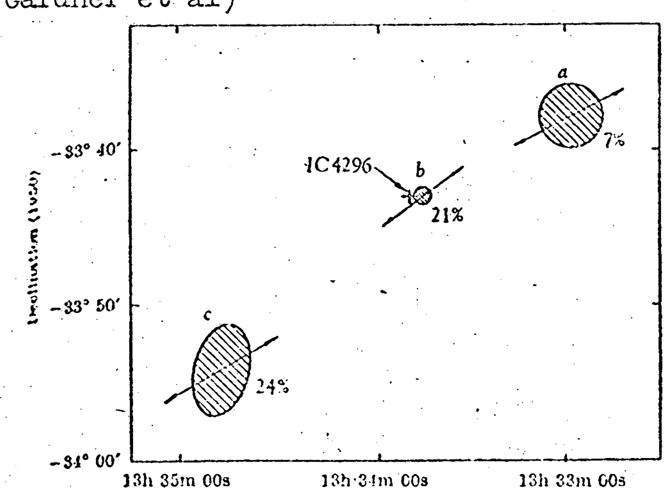


Fig. 1. The structure of 13-33 derived from 11 cm observations: the contours are the half intensity levels of a gaussian distribution fitted to the observations. The position of IC 4296 which is identified with the radio source is also shown. The position angle of the electric vector of the intrinsic polarization (that is, corrected for Faraday rotation) and the 11·3 cm percentage polarization is indicated for each component

Frequency Effects.

Spectral Indices of integrated flux vary over approx. range -0.3 to -1.2 depending on the type of source and the frequency range.

Between 38 and 750 MHz, the unidentified sources and galaxies have steeper spectra than QSOs (-0.79; -0.75 and -0.70 respectively). The non-scintillating sources in 3C list have steeper spectra than the scintillators. There is a high correlation between convex spectra and small scale structure. (Kelleramnn, Pauliny-Toth, Williams 1969).

Bridle and Costain (1970) observed 90 clusters; found spectra for rich clusters -0.926 steeper than for galaxies -0.753.

Thus the larger the source, the steeper is its spectrum in the low frequency range. It is likely that this also holds for the extended components in a single source. Quoting van der Laan (1969) "There is thus no need to assume that the typical difference in spectral index from one component to another in the same source, is less than the difference from one source to another." See also Bridle (1969).

The Coma cluster (Abell 1656) has a core with index -0.8; the halo has index steeper than -1.8 and possibly ~-2.5 so that it dominates below 38 MHz.

Virgo A has a steep index for its halo. Yet Virgo, with Hydra Hercules and 3C353 are recommended as secondary standards (Cass A is primary) for flux measurements because of their simple power law spectra between 38 and 8000 MHz. All these show structure. Even if the integrated flux maintains constant spectral index (no curvature) observations with different beamwidths, or at different frequencies could give flux errors as the extended structure becomes partially resolved.

Because of undetected halos, many low frequency fluxes may be underestimated. The seyfert galaxy NGC 1275 has a concave spectrum with excess flux below 100 MHz (Roger, Costain, Purton 1965)

Except for halo sources (components with common centroid) the structure would change when there are spectral differences between components. Thus centroids and peak positions need not coincide at different frequencies. The problems in searching for optical identifications are obvious.

Identifications.

	Sc So	Ellip	D DB	N Sey	Gal	QSS	BSO	uniden.
Molonglo 92 >3'	5	32	16	2	4	-	-	33
NRAO 1083	9	73	50	30	88	184	21	628

These approximate distributions show that even among the extended sources, 35% remain unidentified. Of the QSOs that have had their structure measured, most are double (or fit a double model) and Hogg (1969) found 6 out of 18 had one component near the optical position (rather than the centroid). These components are usually small diameter and time varying. The distribution in size is shown in the earlier table.

Present searches for optical objects are using positions accurate to 1 or 2"arc but need to allow for shifts from the centroid of up to 1 or 2'.

REFERENCES

Arp, H., Astrophys. Letters, 5, 75, 1970.

Bash, F. N., Ap. J., 152, 375, 1968.

Bash, F. N., Ap. J. Suppl., 16, No. 149, 373, 1968.

Bolton, J. G., Astron. J., 74, 131, 1969.

Bridle, A. H., and Costain, C. H., Astron. J., submitted.

Bridle, A. H., Nature, 224, 889, 1969.

Cameron, M. J., Proc. Astr. Soc. Aust., 1, 229, 1969.

Collins, R. A., and Scott, P. F., Mon. Not. Roy. Astr. Soc., 142, 317, 1969.

DeYoung, D. S., and Axford, W. I., Nature, 216, 129, 1967.

Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., and Archer, S. Mem. Roy. Ast. Soc., 68, 37, 1959.

Ekers, R. D. Aust. J. Phys. Astrophys. Supp., 6, March 1969.

Fomalont, E. B., Ap. J. Supp., 15, No. 138, 203, 1968.

Fomalont, E. B., Ap. J., 157, 1027, 1969.

Fomalont, E. B., Ap. J., 160, L73, 1970.

Gardner, F. F., and Davies, R. D., Nature, 210, 144, 1964.

Hogg, D. E., Ap. J., 155, 1099, 1969.

Kellermann, K. I., Pauliny-Toth, I.I.K., and Williams, P.J.S., Ap. J., 157, 1, 1969.

Macdonald, G. H., Kenderdine, S., and Neville, Ann C., Mon. Not. Roy. Astr. Soc., 138, 259, 1968.

Maltby, P., and Moffet, A. T., Ap. J. Supp., 7, 141, 1962.

Mills, D. M., and Sturrock, P. A., Astrophys. Letters, 5, 105, 1970.

Morimoto, M., and Lockhart, I. A., Proc. Astr. Soc. Aust., 1, 99, 1968.

Rogers, R. S., Costain, C. H., and Purton, C. R., Nature, 207, 62, 1965.

Ryle, M., and Longair, M. S., Mon. Not. Roy. Astr. Soc., 136, 123, 1967.

Schilizzi, R. T., and McAdam, W. B., Proc. Astr. Soc. Aust., 1, 228, 1969.

Schilizzi, R. T., and McAdam, W. B., Proc. Astr. Soc., Aust., 1970.

Taylor, J. H., and DeJong, M. L., Ap. J., 151, 33, 1968.

Van der Laan, H., Astron. & Astrophys., 3, 477, 1969.

Wall, J. V., Cole, D. J., and Milne, D. K., Proc. Astr. Soc. Aust., 1, 98, 1968.

Wyndham, J. D., Ap. J., 144, 459, 1966.

Kell.