INTRODUCTORY LECTURE

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On the subject of radiogalaxies my most vivid reminiscence is of an afternoon in Santa Barbara Street with a marvellous meeting with Baade and Minkowski where they told me that they had discovered that Cygnus A had been identified with a faint galaxy.

What a perspective did this open for penetration to distances far beyond our reach up to that date, distances where effects of the structure of the Universe must become wonderfully important!

The deep impression made by this discovery was only to be rivaled by that felt when a few years later Ryle and his co-workers actually penetrated through observations of radio sources into a past when the Universe was *actually* different from the present.

New discoveries thereafter succeeded each other in rapid succession: The discovery by Moffet at Owens Valley of the large *double* structure of radio galaxies; the discovery of the polarization and the synchrotron nature of their radio emission; and next the discovery of the quasars by Schmidt and Greenstein. The quasars gave great expectations for cosmology. But they did more: they also opened our eyes to the essential role which extremely small and massive nuclei might play in the formation of large radio sources.

That these cores must be very *massive* is demonstrated by the often tremendous radio as well as X-ray powers of the radio galaxies. They must also be *small*, as is shown by the frequent occurrence of flat spectra and by the large variations in brightness and polarization on time scales of days (and sometimes even *hours*, as in the X-ray emission from NGC 5128). Perhaps the most conspicuous property of the core engines that produce the energy for the radio galaxies is their directionality as evidenced by the mostly two-sided radio lobes and the jets leading to them. This has led to the idea that the central engines would be rotating black holes surrounded by accretion disks. However, no massive black holes have ever been observed, and it remains possible that the actual source is something else.

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Evidently it would be important to find *direct dynamical evidence* for nuclear black holes, and to determine their masses. So far the attempts have been unsuccessful. A few years ago it looked as if an increase in the velocity dispersion near the centre of M87 indicated the presence of a non-luminous central mass of roughly 3×10^9 $M_\odot$; but later observations did not confirm this. They only indicated an upper limit of about 1×10^9 $M_\odot$. Apparently, the Space Telescope will be needed to determine the mass of M87's central engine. That will be an exciting programme, which can doubtlessly be extended to other radio galaxies.

The gradual loss by radio galaxies as well as quasars of their status as an entirely separate class of objects has been an intriguing development. More and more evidence has shown their *resemblance to other types* of active galaxies, in the first place the Seyfert systems, which may have the same sort of central machine, but of smaller power. Double and triple structures closely resembling that of radio galaxies but on two orders of magnitude smaller scale have been discovered in several Seyfert spirals (Wilson & Willis 1980); this shows that they have collimated ejection.

Shklovskii (1978) has suggested that a mass measurement might be possible for the nucleus of NGC 1275. At 1.35 cm the nucleus is double, with a separation of $0\overset{''}{.}0014$, or 0.5 pc. The optical spectrum suggests that the N_1, N_2 and H_β emission lines might consist of two components whose velocities differ by about 800 km s^{-1}. Combination of these data led Shklovskii to a, clearly very hypothetical, mass estimate for the nucleus, of about 3×10^8 $M_\odot$, and to the suggestion that this may represent the mass of a central black hole.

A binary nucleus might also offer an explanation of the unusual further milliarcsec structure (Matveyenko *et al* 1980) and the equally unusual radio features in the 1-7 kpc range found by Noordam & de Bruyn (1981) after they had succeeded to subtract the bright central point source (Figure 1).

As it might well be that all large galaxies pass intermittently through stages of Seyfert activity it seemed possible that they all possess the same potency for a high energy production in their nuclei. It becomes meaningful then to extend the quest for massive black holes also to ordinary galaxies. Again, the Space Telescope may provide the means. In this connection it is intriguing that Seyfert-like activity has recently been found in the ultra-compact nucleus of M81 (cf. Peimbert & Peimbert 1981).

In connection with what I have just said I want to turn your attention for a few moments to the *centre of our Galaxy*. Here we do not need the extreme resolution of the Space Telescope to penetrate to the core.

In principle the existence of a dark mass in the centre can be discovered if from the motions and density distribution of objects very close to the centre the total mass within, say, 0.5 pc can be determined.

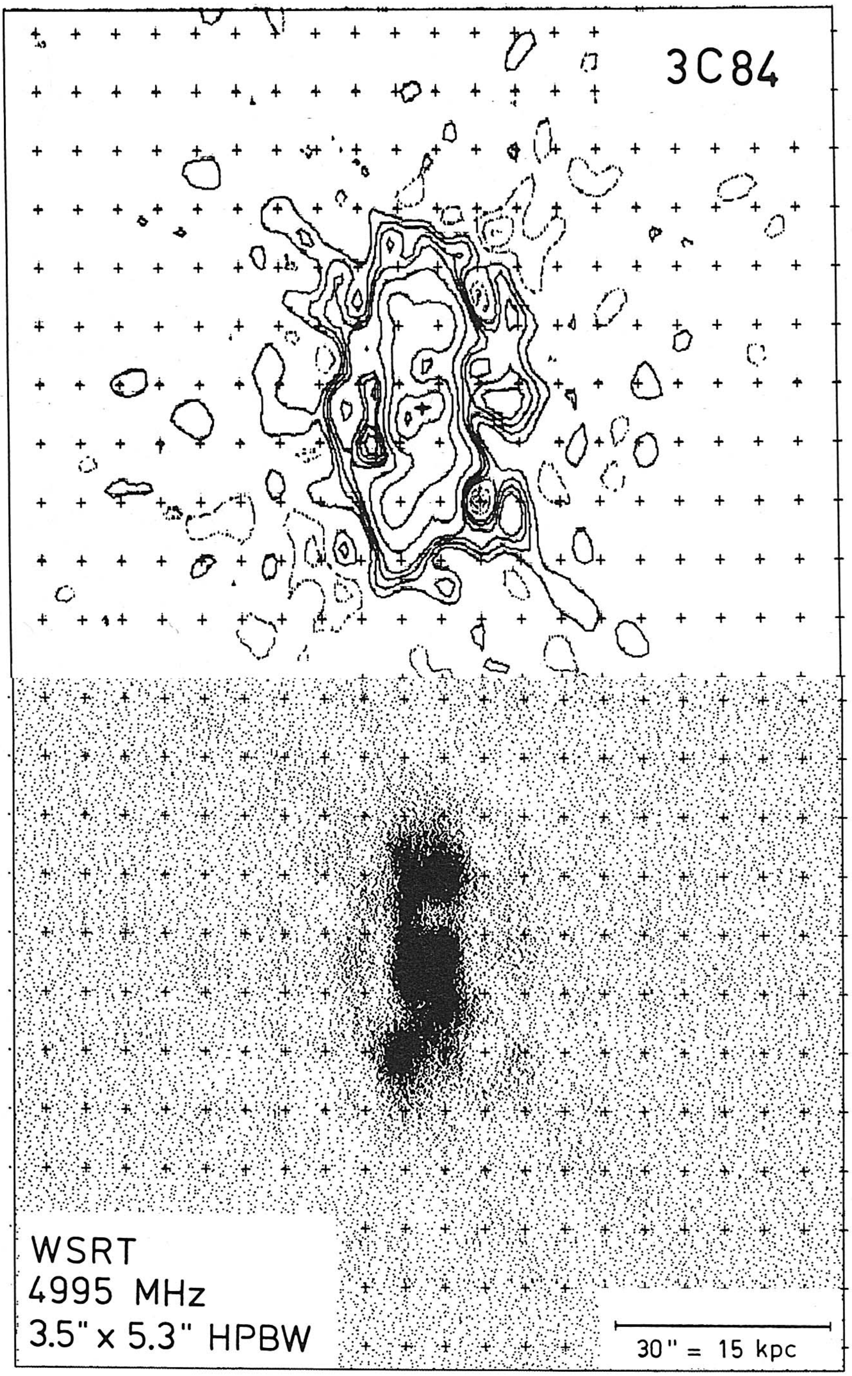

Figure 1. 3C 84 = NGC 1275 at 6 cm after "removal" of 59600 mJy core at + sign. Lowest contours about 1/36000th of original peak. North is on top, East to the left. Below: radio picture (Noordam & de Bruyn 1981).

Members of Townes' group have attempted to do this from the dozen fast moving clumps of ionized gas which they discovered in the 12.8-μ NeII fine structure line. Their observations indicated a total mass of 5.4 x 10^6 $M_\odot$ within 0.5 pc (cf. Lacy *et al* 1979, 1980). The total *stellar* mass within this radius may be inferred from the 2.2-μ radiation as measured by Becklin & Neugebauer (1968). This gives 2.0 x 10^6 $M_\odot$ (Sanders & Lowinger 1972; Oort 1977). The comparison between the two numbers shows that there might be a central black hole of 3 x 10^6 $M_\odot$. Clearly the reasoning leading to this result involves some quite uncertain suppositions; the outcome is therefore no more than a marginal indication that a black hole with a mass of at most ∿ 3 x 10^6 $M_\odot$ might be present.

The fast moving clumps present several interesting problems. What is their origin? What causes their rather peculiar state of ionization, and what happens with the large quantity of gas produced by their decay? As Lacy *et al* (1980) point out a black hole may help to solve these problems, but alternative solutions also exist.

A further interesting feature at the galactic centre is the radio source Sgr A West, and the extremely compact source contained in it (diameter ∿ 80 light-minutes). This source lies within 1 or 2" from the dynamical centre indicated by the NeII observations; it is still uncertain whether the two positions co-incide exactly.

The galactic centre appears also to be a remarkably strong source of radiation in the positron-electron annihilation line at 511 keV. It is unknown how the large quantity of positions is produced; but the NeII clumps provide suitable regions for their annihilation, and give a natural explanation of the unexpected narrowness (half width 2 keV) of the observed line. It has been claimed that the γ-radiation at 511 keV is variable on a time scale of the order of half a year. Confirmation of this variability would evidently be of utmost importance. It is a desideratum deserving highest priority (Riegler *et al* 1982 and ref. therein).

In the further surroundings of the centre there are a number of large expanding features, partly in molecular form, partly in HI. The masses involved are or the order of 10^8 $M_\odot$. The molecular clouds lie in an inclined layer making a considerable angle with the galactic plane.

The cause of the anomalous motions and positions is still uncertain. One possibility is that they are due to expulsion from the surroundings of a rotating black hole whose axis makes a large angle with the galactic axis. Such a possibility is suggested by what we observe on a much grander scale in radio galaxies, where ejection of large masses in directions making large angles with the symmetry axis of the central galaxy is not uncommon. It is still more strongly suggested by the anomalous arms observed in NGC 4258 (see below) which are believed to be due to expulsion from the nucleus in two opposite directions in the equatorial plane of this spiral or at small angles with it. In this case the anomalous arms are ionized, and they emit synchrotron radiation, which is not observed in our Galaxy.

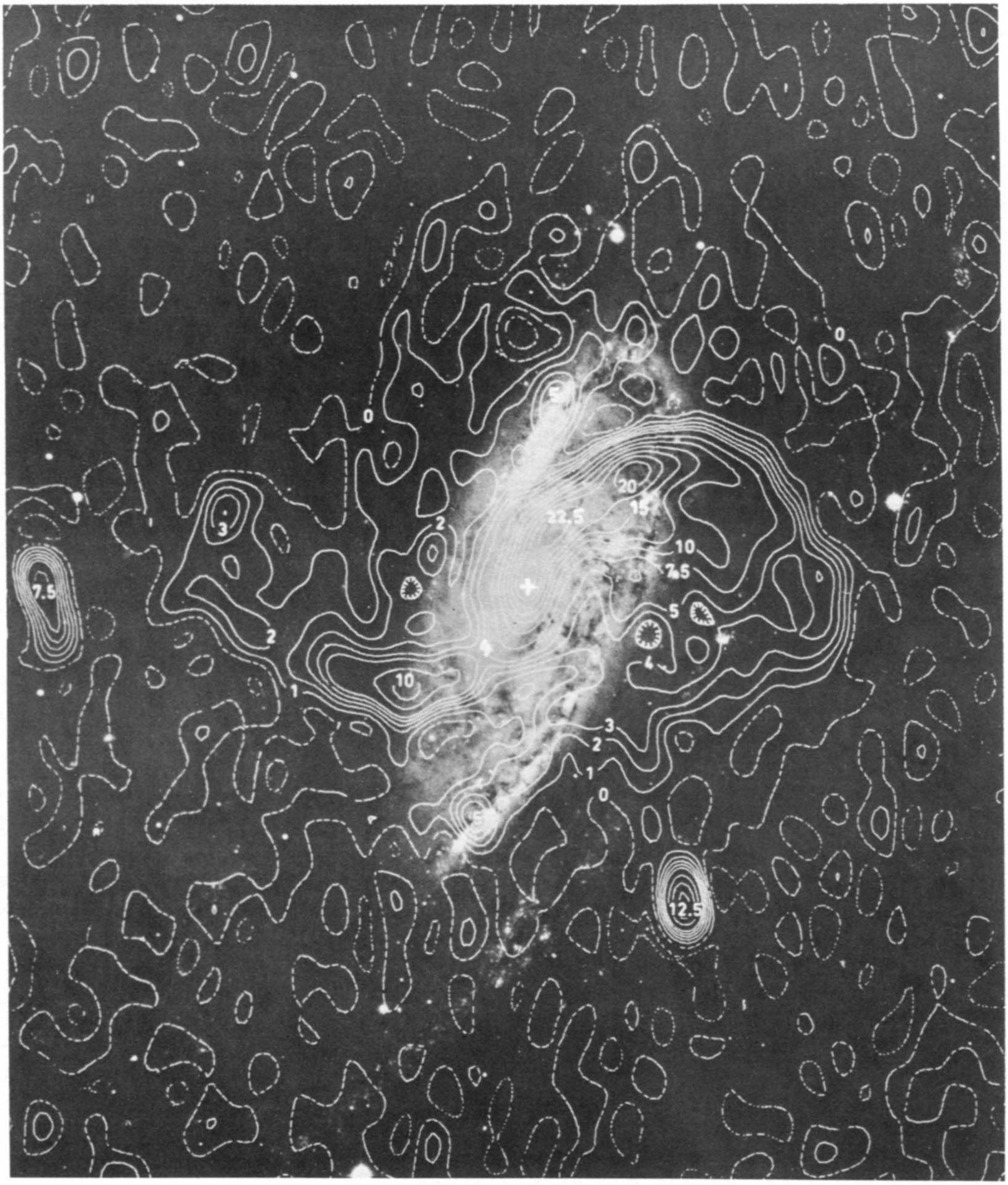

Figure 2. NGC 4258, with radio contours at 1415 MHz. Contour units 0.9 ^{o}K brightness temperature. Scale 1 cm = 48". The position of the optical nucleus is indicated by a white cross (van der Kruit et al 1972).

In the case of our Galaxy alternative interpretations may be possible, such as that suggested by Burton & Liszt, who interpret the observations by a kinematic model involving strongly excentric orbits (Liszt & Burton 1980).

That large masses of gas are sometimes expelled from the nuclei of "common" galaxies is amply shown by the Seyfert phenomena, but in particular also by NGC 4258. This is a bright spiral, at an estimated distance of 6.6 Mpc, which in optical appearance does not differ in any way from a normal massive Sbc system, with an indication of a central bar. However, when observed in the radio continuum it shows a most remarkable spiral-like structure of synchrotron emission which cuts almost perpendicularly through the optical spiral arms, and extends to the outermost limit of the gaseous disk (Figure 2). In the inner part the anomalous arms continue as thin filamentary HII arms right into the core (cf. Courtès & Cruvellier 1961; van der Kruit *et al* 1972; van Albada 1978, 1980). The anomalous arms are probably produced by two opposite streams of gas ejected from the nucleus which interact with the disk gas of the spiral, the synchrotron emission being due either to the ejected plasma itself, or to compression of the disk magnetic field, or to re-acceleration of relativistic particles in the shocks caused by the ejected gas. From an extremely crude model of the ejection it was found that between 10^7 and 10^8 solar masses of gas should have been ejected 20 - 40 million years ago at velocities ranging from 800 - 1600 km s^{-1}. Van Albada (1978) has pointed out that there is evidence of intermittent ejection, beginning with a large eruption about 40 million years ago and continuing in the same direction almost up to the present. As he mentions, there is some similarity with the ejections that give rise to head-tail radio galaxies, as well as to the common collimated double radio sources. In the most extensively studied head-tail galaxy, NGC 1265, the total mass in the tail has been estimated at 5×10^8 $M_\odot$ (Miley *et al* 1975), roughly an order of magnitude larger than the ejected mass in NGC 4258; for the ejection velocities values of 9000 km s^{-1} have been suggested in a model discussed by Owen *et al* (1978), again considerably higher than those which seem to have occurred in NGC 4258.

One reason why the peculiar phenomena that are so striking in NGC 4258 do not occur more often in spirals may be that they can occur only when the axis of ejection (presumably the rotation axis of the central black hole's accretion disk) is almost perpendicular to the rotation axis of the galaxy.

As there is no sign of any present activity in the nucleus of NGC 4258 the ejection has now probably ceased.

A closer comparison with radio galaxies will have to await better models, for which calculations are presently being made by van Albada (1981).

NGC 1275 may, in a way, be similar to NGC 4258 in the queer shaped anomalous synchrotron emission pattern shown in Figure 1.

Most interesting evidence showing that nuclei of some *normal* E and So galaxies eject matter - or at least relativistic particles - in narrow cones extending from $\sim$ 1 pc to kpcs has recently been given by Jones, Sramek & Terzian (1981). The observations strongly suggest that these galaxies contain something like black holes with rotating accretion disks. They also suggest that these might be of common occurrence.

I must now turn to the radio galaxies proper. Having never done any direct research in this field I feel very little qualified to introduce the subject to an audience of experts. The only justification I can claim is that my lack of specialist knowledge makes me free from preoccupation with any particular aspect.

Let me therefore give a list of some of the principal problems (see next page) as they present themselves to a greatly interested outsider, who hopes to get a little understanding of many of these questions in the present conference.

For the problems of cores and jets reference should be made to a most illuminating review prepared by Rees *et al* (1981) for the Tenth Texas Symposium on Relativistic Astrophysics (December 1980).

It seems that the best information on problem 14 will come from the tailed radio galaxies, where the approximately known motion of the galaxy relative to the cluster gas gives us a hold on the travel times through the tails. Combination with density estimates from Faraday rotation yields a rough idea of the flow. The, still quite uncertain, present data indicate flows of the order of 1 $M_\odot$ per year.

Finally, the problem of *evolution*. This is perhaps the most important subject connected with quasars and radio galaxies: their own evolution, and the evolution of the galaxies from which they emerge (on this latter very interesting question (cf. Katgert *et al* 1979) I want to refer to a communication to be presented by Windhorst, Kron & Koo).
The enormous increase in number density of quasars with increasing redshift must reflect the birth rates of galaxies. It also indicates that the quasar phenomenon develops during the galaxy's youth, and lasts only a small fraction of its lifetime. From the steepness of the drop in proper density between $z \sim 2$ and $z \sim 1$ we may conclude that the average duration of the quasar cannot be longer than 10^8-10^9 years.

The very large number density of quasars in the past may indicate that a large fraction of large ellipticals - if not all - have gone through a quasar stage and therefore contain a massive "black hole".

Recent observations indicate that *non-quasar radio galaxies* show similar strong evolution effects. They may well be descendants of the early quasars. The fact that old elliptical galaxies are sometimes fairly strong radio emitters shows that radio emission is either recurrent, or that it can last during the whole life of an elliptical up to the present time (possibly due to situation in the centre of a cluster?).

A LIST OF QUESTIONS

Problem	Sub-problems	Suggested answers
THE CENTRAL ENGINE		
1. total energy	energy of relativistic protrons? equipartition? source life times? γ-ray power of 3C273	accretion by massive compact objects; how massive? (up to 10^9-10^{10} $M_\odot$?)
2. formation of "black holes"	prevention of fragmentation; disposal of excess angular momentum? restriction in mass? does b.h. form galaxy or does galaxy form b.h.?	Rees, I.A.U. Symp. No. 77, p.239. or: primordial black holes
3. expulsion in narrow cones		"nozzle"; but how to explain milliarcsec jets in same direction?
4. origin of accreting matter	infalling gas must get rid of angular momentum; must its spin axis coincide with that of black hole? how are "loss-cone" orbits refilled?	infall of cooling gas from surrounding cluster; merging galaxies; dynamical instability of galaxy.
5. why do strong radio sources always originate in ellipticals and never in spirals?		difference in gaseous environment?
6. long-term constancy of beam direction	divergences of radio axes from gal. minor axes, and probably also from *rotation* axes; how much matter must flow into nucleus during life of collimated structure?	rotation of very massive "black hole"

7. Z-shape and cross-like sources		precession of rot. axis; caused by binary black hole? (which must then be fairly common); in some cases vel. gradient in intergal. medium
THE NUCLEAR REGION ($\lesssim$ 1 pc)		
8. variability on time scales of hours to years (optical, radio, X-ray; polarization)	longer-term (10-20 y) decrease in brightness; variation at low frequency	outbursts; possibly, absorbing nuclear clouds (but how can these exist?)
9. superluminal expansion	is it restricted to cases of beams near line of sight?	ultra-relativistic ejection; or beam sweeping over screen
10. milliarcsec (pc) jets	are they always one-sided?	ultra-relativistic
JETS		
11. why do we see so many one-sided jets (M87, 3C273, NGC 6215, NGC 315, etc.?)	intrinsic one-sided ejection; visibility of jet by interaction with intergalactic medium	ultra-relativistic velocity (M87?); cloud structure in core; asymmetry of intergalactic medium.
12. why are ∿ 1/5 of radio quasars one-sided?		
13. anomalous optical jet in DA 240	large angle with radio axis; 3000 km s^{-1} vel.? (is jet stellar?)	merger?
EXPULSION AND ACCRETION		
14. rate and velocity of expelled matter		from tailed sources: vel. 1000-10000 km s^{-1}; ∿ 1 $M_{\odot}$ per year?

RECURRENCE OF NUCLEAR ACTIVITY		
15. multiple lobes in radio galaxies	what causes recurrence?	dynamical instability of galaxy; mergers
16. what evidence do Seyfert galaxies give?		percentage Seyferts
17. what is time scale?		10^6 - 10^8 years? Activity in NGC 4258 may indicate similar time scale
18. is quasar stage recurrent?	how long does it last?	steep increase in number density suggests occurrence in youth of galaxies, and life times < 0.01 Hubble time
NORMAL GALAXIES		
19. do all massive galaxies go through Seyfert stage(s)?		
20. have they all gone through quasar stage?		quite possibly, in view of past frequency of quasars and present numbers of giant ellipticals
21. do most, or all major galaxies have central "black holes" (10^6 - 10^8 $M_\odot$)?		Space Telescope (M87, M31, M81, ..)

In this connection my last question is: Do all massive ellipticals go through one or more quasar or radio galaxy stages? If not, and radio emission is therefore a characteristic of only a fraction of the massive E galaxies, what gives them this distinction?

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