QUASARS: CURRENT PROBLEMS

Jean Eilek

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PART THE FIRST: SOME IMPORTANT FACTS

I. Definition and history

1960 — 3C48 identified with starlike optical source;
1963 — 3C273 likewise; broad emission lines identified at $z = 0.158$
($z = 0.367$ for 3C48, the same year)

Definition from Schmidt, 1964:

a. starlike, identified with radio source
b. variable
c. large UV excess
d. broad emission lines at high redshift

Today, several hundred are known, out to $z = 3.53$. We only need to revise Schmidt's definition a bit:

a. starlike, may be (10%) a strong radio source
b. unchanged
c. probably nonthermal optical continuum; also X ray source
d. also with narrow absorption lines at lower redshift

Point: that out understanding of the phenomenon is but little advanced over the early sixties, despite much observational and theoretical effort. Still a botanical approach -- observe and classify.

II. Continuous spectrum (probably from the region close to the central machine)

1. X rays (HEAO/Einstein Observatory): many qso's, radio strong and radio quiet, seen; $L_x \sim 10^{43}$ to 10^{47} ergs/s @ .5 - 4 keV. Many Seyfert and radio galaxy nuclei seen also. Spectra, when seen, appear power law, $f(\nu) \propto \nu^{-\alpha}$, out to, say, 100 keV. Variable over $\Delta t \sim$ days → small.

   People are tending to agree that the X rays arise from inverse Compton scattering of softer photons.

   Also, γ rays seen from a few objects; most of the total luminosity from a typical quasar may be in the X and γ ray bands.

2. Optical/infrared: usually looks to be a power law; $\alpha_{opt} \sim 0.5 - 1.5$ usually, may be as steep as 6.0. Evidence for reddening.

   Optically Violent Variables: few %; $\Delta t \sim$ days; polarization $\sim$ 10 - 35 %. Polarization, direction of polarization, magnitude all vary.

   non-OVV's: may vary over $\Delta t \sim$ years, or not at all; polarization $\sim$ 1 %; spectrum may not be power law.

   Origin of optical/IR continuum? May be synchrotron; synchrotron self Compton; thermal emission and/or dust; mixture of all of these.

3. Radio: 5 - 10 % of optically selected objects are radio strong, with compact core + (often) extended structure.

radio strong : $L_{rad} \gtrsim 10^{-1} L_{opt}$ (ergs/s)
radio quiet : $L_{rad} << L_{opt}$

apparently a strong distinction, not a continuum

Core often variable;
generally assumed to be synchrotron emission;
VLBI → small, linear core structure; apparent superlight expansion

Self absorption seen at low radio frequencies; can derive source parameters:

$B \sim 10^{-4} - 10^{-2}$ G
$U \sim 10^{53} - 10^{57}$ erg, total energy
size < 1 pc

$\frac{u_{rel}}{u_{mag}} \sim 10 - 10^6$; particle dominated

$\frac{u_{rad}}{u_{mag}} \sim 1 - 10^3$; Compton problem

4. Variability: Perry (1976) tried to classify types of variability:

   a. short term flucuations (< 1 day)
   b. long term flucuations (∿ years)
   c. Combination of (a) and (b)
   d. other

Variability at different frequencies usually uncorrelated. Polarization also varies.

5. Inverse Compton Problem:

Variability, VLBI → small size; this + high luminosity → high radiation density and high electron density.

a. optical depth to synchrotron photons > 1 → inverse Compton scattering should turn almost all radio photons into higher energy, optical or X ray. Predicts almost no radio emission.

b. High radiation density → electrons lose energy to Compton scattering; reacceleration needed.

III. Line spectra

1. Emission lines (probably arise in extended atmosphere, 1 - 100 pc)

   a. Permitted lines: broad ($\Delta v_{int} \sim 10^4$ km/s) with internal "cloudlike" structure. Often asymmetrical. H, He, C IV, Mg II, Fe II . . . Occasionally with narrow core, though this is often weak in QSO's.

   b. Forbidden lines: O III, Ne V, O II . . . Resemble narrow cores of Balmer lines, with $\Delta v_{int} \sim 10^3$ km/s.

   c. No definite cases of line variability, but a few single events have been reported. Little monitoring. (Sometimes lines are seen to hold steady when continuum varies.)

2. Absorption lines

   a. Seen in a few low-z objects (may not be in observable part of the spectrum; IUE found Ly α absorption in various objects). Most high-z quasars show several absorption systems, having distinct redshifts, almost always less then the emissios redshift.

b. z(abs) << z(em) in many cases, indicating a high velocity of the absorbing material towards us, away from the quasar. Can be as high as 0.7 c, although more typical values are $10^3 - 10^4$ km/s.

c. Multiple systems are found in many objects, with z(em) - z(abs) ranging from, say, 0.1 to 2.0. A range of ionization states is seen within one system: c II, Si II, N V, Ly α . . . Also 21 cm absorption is found a the same redshift as an optical absorption system, in 3C286, AO 0235+164, 1331+170. Also many lined (hundreds) to the blue of Ly α, which may be optically thin clouds.

d. Very narrow lines: $\Delta v_{int} \sim 10$ km/s (on the order of the sound speed in a gas at 10^4 K) -- which size may be resolution limited still. (Exceptions: P Cyg profiles -- broad absorption troughs, $\Delta v \sim 10^3$ km/s, which surely come from a smooth outflow -- are seen in ten or so.)

3. Lyman continuum absorption? the data is still scanty; this is apparently seen in a few objects as the emission-line redshift (as if we were seeing the continuum source through the emission-line clouds); in a few others there is no evidence of the Lyman edge at the expected redshift.

IV. Relation to other active nuclei

1. Seyfert nuclei (usually spiral galaxies)

Share broad optical emission lines and (in Seyfert 1's) the nonthermal continuum; X ray sources, usually radio weak, with an extended (100 pc) low luminosity source, no core.

2. Radio galaxy nuclei (usually elloptical galaxies)

Optical spectra akin to that of Seyferts; radio source strong and double , sometimes with compact core.

3. Lacertids

Starlike, with very weak spectral features and surrounding nebulosity which shows stellar absorption lines (cD galaxies??). Violently variable, highly polarized.

PART THE SECOND: CURRENT PROBLEMS

I. State of the atmosphere

1. Current conception of the geometry:

A very small core with continuous emissions (X ray, optical/IR, radio) which contains the (unspecified) energy source; plus

an extended atmosphere with line emitting gas in clumps (most likely transient), perhaps in a hotter intercloud medium (which could be the extended, low-luminosity radio source). These clumps may or may not be the origin of the absorption lines.

2. Thermal state:

Forbidden line ratios require density of 10^4 cm^{-3}, $T \sim 10^4$ K. Broad permitted lined must arise in gas with $10^{10} > n > 10^7$ (based on quenching density for forbidden lines).

This gas is assumed to be photoionized by high energy photons from the central source. Detailed calculations can explain line ratios fairly well if Balmer line self absorption and dust reddening is included, and if the optical continuum is extrapolated to higher energies.

3. Dynamics

One wants to explain the linewidths for the emission lines, as well as the high velocities of the absorption lines (if, indeed, they arise close to the qso).

Clouds of line emitting gas will feel radiation pressure from the central source -- enough to explain the narrower linewidths but not the broadest lines or the high absorption cloud velocity. A "hot" expanding wind (either driven by relativistic particles, or shock heated) in which clouds condense (from thermal instabilities) may work.

Alternatively: velocities may be due to infall -- accretion onto a massive central object -- or rotation or random motions. Less work has been done on such schemes.

II. Origin of the absorption

1. Due to intervening stuff? This would account for the high velocity,due to the Hubble expansion; also, one definitely confirmed case would establish the cosmological nature of the QSO's. However, this requires <u>many</u> intervening (proto?)galaxies, which have apparently "normal" heavy element abundances, and some high ionization states.

2. Physical conditions in the absorbing gas: the weakness of collisionally excited fine structure lines requires densities below 10^3 cm^{-3}; this along with photoionization calculations (if the gas is ionized by the central source, as is the emission line gas) require the absorbing clouds be at least kpc away from the center. (However, recent work by Sarazin suggests this may not be so if the clouds are optically thick.)

3. It has been suggested, in support of the intervening-stuff hypothesis, that it is difficult to accelerate gas to such high velocities (see I.3 above) while maintaining low internal velocities -- $\Delta v_{int}/v_{ej} \sim 10^{-3}$. However, this ratio also holds for nova ejecta, which clearly have been accelerated by the nova!

4. Statistics of galaxy and protogalaxy sizes and spatial densities are clearly important, and as yet not very well known (notwithstanding the large number of papers pro and con the question).
Burbidge (1977) calculated galactic coronae of size 50 - 100 kpc were needed to explain the observed frequency of absorption systems.
Note also, identification of lines or systems in a given object, let alone a complete sample, is very difficult and somewhat subjective.

5. Those QSO's with z(abs) ∿ z(em), and those with P Cyg profiles, are generally accepted as being local to the QSO; the few 21 cm lines with $\Delta v_{int} \sim 5$ km/s and dimensions tens of kpc, are almost surely intervening; as for the rest . . .

III. What is the distinction between radio strong and radio quiet?

There is no correlation of this with any other property that I know of: optical luminosity, emission line properties, X rays all seem indistinguishable between radio strong and radio quiet. OVV's tend to be radio strong; but not all radio strong objects are violently variable.

Why? Obscuration or absorption of radio source by the atmosphere?
Are the relativistic particles simply absent in most QSO's?
Is it an effect of beaming or other special geometry?
Are the two types of objects totally different?

IV. The nature of the central machine

Burbidge in a 1967 review listed current models:

supernova clusters
stellar collisions
massive objects
quarks/matter creation
matter/antimatter annihilation
gravitational focusing of light from faint background objects

The first three are still with us. Rees (1976) lists

dense star clusters
massive pulsars-spinars
accretion onto a massive black hole.

All of these are currently under investigation, with the black hole model being the most fashionable (and, to be fair, the most promising in a pretty poor field).

A model must account for:

high luminosity from a small region (10^{48} ergs/sec, under 1 pc)
variability: $\Delta L/L \sim 1$
a unique, remembered axis for plasma ejection and high collimation
origin and acceleration of the relativistic material
details of the emission processes

None of the models as yet interface well with the atmosphere models or with the wealth of observational bits and pieces.

Recent reviews:

Physica Scripta, 1978, Proceedings of 1977 Copenhagen QSO/active nuclei conf.
Proceedings of BL Lac conference, Pittsburch, 1978.
Rees, "Quasar Theories", 1976 "Texas" conference on relativistic Astrophysics
Weedman, 1977. A.R.A.A., "Seyfert Galaxies"
Strittmatter and Williams, 1976, A.R.A.A., "Line Spectra of QSO's"

(Observatory)

QUASARS

By Martin J. Rees
University of Cambridge

[The Halley Lecture for 1978. Delivered in Oxford, 1978 May 2]

Vice-Chancellor, Ladies and Gentlemen:

The last 15 years have seen an unprecedented advance in the range and scope of astronomical investigations. This accelerated progress is owed to improved instrumentation, to the exploitation of new parts of the electromagnetic spectrum (particularly in radio astronomy) and to the advent of space techniques. Our view of the cosmic scene is less biassed and incomplete than it was when one studied only those objects that shine in visible light, and the general vocabulary has been enlivened by such concepts as pulsars, neutron stars, quasars, black holes, and the big bang. The credit for these advances lies with observers and experimenters. So little is yet properly explained that we theoretical astrophysicists should feel deeply inadequate and inferior. But the frontiers of current research are, almost by definition, in the murky penumbra where we are still groping for even a qualitative understanding of what is going on.

My lecture today will focus on quasars, and the various phenomena that seem related to them. All entail a massive outpouring of energy from the nuclei of galaxies, powered by something more exotic than stars, which gives rise to the most luminous objects yet recorded in the radio, optical, or X-ray bands. The data are only just beginning to fit into some kind of pattern, but the issues they raise seem of central importance for extragalactic astronomy, and potentially for cosmology and gravitation theory as well.

HISTORY

The first clues that there might be more in the Universe than ordinary galaxies, and that galaxies might be more than just self-gravitating aggregates of ordinary stars, came from the radio astronomers. In 1954 Baade and Minkowski showed that the radio source Cygnus A, the second most intense object in the radio sky, was associated with a remote galaxy with a redshift of 0·05. This immediately implied that some peculiar galaxies might be detectable by radio techniques even if they were so far away that the integrated light from 10^{11} stars failed to register optically. Radio maps made with modern aperture-synthesis telescopes tell us that the emission from a source like Cygnus A comes from two blobs symmetrically disposed on either side of the central galaxy. This double structure, in which the overall separation of the components may be a million light-years or even more, seems characteristic of the strongest radio sources, and I shall return to its interpretation later. It was recognized in the 1950s that the radio emission resulted from synchrotron radiation by relativistic electrons in magnetic fields. In a celebrated paper published in 1959, Burbidge estimated that the minimum energy content of the radio lobes of an extended source might correspond to that released by the complete annihilation of a million solar masses of material. This was the first indication that in galactic nuclei events occur that release energy on scales vastly exceeding even a supernova explosion, and that somehow this energy is channelled primarily into the form of relativistic plasma and magnetic fields.

The major contribution of optical astronomy to this story came in 1963, when attempts to discover the optical counterparts of some radio sources led to the recognition that the Universe contained an unsuspected new class of objects, which looked like ordinary stars on photographic plates, but whose spectra displayed emission lines with large redshifts. These objects, the quasars, have optical luminosities exceeding those of normal galaxies even though they are much more compact. Moreover the light seems to be emitted by the same process, synchrotron radiation, as the radio output from strong sources such as Cygnus A.

THE BASIC FACTS

Hundreds of quasars and quasar-like objects have now been discovered. Indeed the catalogues contain a whole zoo of objects with a confusing array of names. They have been discovered by different techniques—by searching for optical counterparts of radio sources, by finding starlike objects with anomalous colours, by finding objects whose light is polarized, or by discovering objects with large redshifts on objective-prism plates. The record quasar redshift stands at 3·53, implying that for this object, OQ 172, wavelengths are stretched by more than a factor $4\frac{1}{2}$ between emission and reception. The most prominent emission features in optical spectra displaying such redshifts are the Lyman lines of hydrogen, which are normally in the far ultraviolet. Spectra of quasars taken with sufficiently high resolution generally reveal enormous numbers of narrow absorption lines. These features indicate that there are large numbers of small clouds of gas, with different redshifts, somewhere along our line of sight to the quasar.

I shall not comment further on the interpretation of quasar spectra, nor enter the lively controversy surrounding the interpretation of the absorption lines. There is not yet any generally agreed classification scheme for categorizing the various classes of quasars. It is, however, a tenable and widely accepted hypothesis that quasars are, in effect, optically hyperactive galactic nuclei, in which non-stellar light from the nucleus outshines the rest of the galaxy by a factor of up to a hundred or more. Quasars are thus detectable even when they are so far away that no trace of the surrounding galaxy can be seen. There is a manifest continuity in properties between quasars and other objects such as Seyfert galaxies. These also presumably involve processes in the galactic nucleus where the star and gas density is high at the centre of the gravitational potential well.

Not only are the quasars a heterogeneous set of objects, but each one may involve a variety of phenomena on different length scales. The radio-emitting regions are large enough to be resolved. The extended radio structure can sometimes be mapped in detail, and even the smallest radio components can often be resolved by the technique of very long baseline interferometry. Much of the action at higher frequencies, however, is concentrated in a region less than one light year across, corresponding to only 10^{-4} arc seconds at a cosmological distance. Even though the absorption lines (and perhaps the *narrow* emission lines) come from a larger region, the *broad* emission lines probably come from gas occupying a region a light-week or so across. A simple thermodynamic argument shows in fact that the region cannot be smaller than this: the lines seen in the spectra tell us that the relevant gas is at a temperature of about 10,000 degrees, and the observed luminosity could not come from a region smaller than this even if it radiated like a perfect black body at such a temperature. The gas seems to be energized by continuum synchrotron radiation, of much higher brightness temperature, emerging from a region only one light-day across. The most fundamental problem posed by the quasars is to understand the nature of this small central primary energy source.

The difficulties are perhaps posed in the most acute form by objects such as AO 0235+164. In the autumn of 1975 this object, which has a redshift exceeding 0·85, was observed to undergo an outburst in both the radio and optical bands. Within a few weeks, its luminosity, if the object radiated isotropically, must have increased by an amount of order 10^{48} ergs per second, equivalent to ten thousand times the entire power output of our Galaxy. It is in objects such as this that one is seeing the most direct and spectacular manifestations of the general quasar phenomenon. Other observable effects, for instance the optical spectra or the extended radio structure, presumably depend on the character of the surrounding galaxy and the gaseous environment, but the central engine may be the same in all cases.

PHYSICAL INFERENCES

What sort of thing could a conventional physicist infer about the nature of the energy supply? It is obvious that one is dealing with a large mass concentrated in a small space. In the diagram now on the screen [and reproduced here—ED.], Figure 1, I have tried to indicate schematically the general arguments which demonstrate the likely increasing dominance of gravity, and the increasing inevitability of collapse, as one considers progressively larger masses. This diagram, which plots as a function of mass the possible equilibrium radius of a gravitating sphere, in fact encapsulates the essential features of much of stellar physics. A sufficiently small mass—an asteroid for instance—is of course essentially unaffected by self-gravity, and can exist as a straight-forward solid at ordinary densities. For an object of planetary mass, self-gravitation starts to become significant. A mass exceeding that of Jupiter, if it were cold, would be crushed to a density exceeding that of a normal solid. It would then be supported by the degeneracy pressure of electrons which are packed closer together (and whose energies are thus correspondingly higher) than in ordinary solids. White dwarf stars lie in this range of masses: the radius decreases as mass increases until the critical Chandrasekhar mass is reached. Above this mass, which is equivalent to about 10^{57} proton masses, no body can escape collapse unless it is hot. Main-sequence stars, burning hydrogen, have roughly the mass–radius relationship shown on the diagram. As Eddington was the first to realize, a self-gravitating hot object exceeding a hundred solar masses or thereabouts is supported primarily by radiation pressure rather than gas pressure. This makes it rather unstable, and also means that it must contract to a smaller radius before getting hot enough to ignite nuclear fuel. This means that stable stars can exist only in a relatively small range of masses. Moreover any very large mass (more than a million solar masses, for instance) seems fated to undergo complete gravitational collapse before any nuclear energy is released at all. Detailed work confirms these general trends. Even though rotation may exert some stabilizing influence, a gravitating object exceeding a million solar masses is so fragile that it seems fated quickly to collapse. According to a theory of gravity such as general relativity it would turn into a black hole.

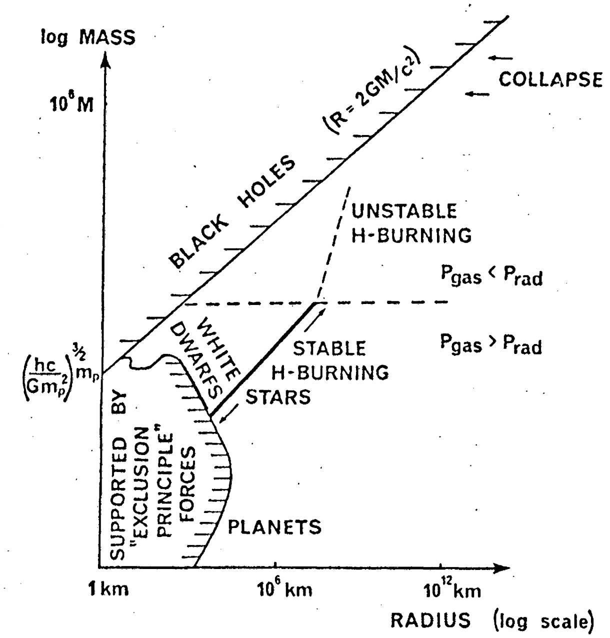

FIG. 1
Mass-radius relationship for self-gravitating spheres.

This might seem a depressing conclusion if one is aiming to account for the colossal energy output from quasars. If, however, a massive black hole is able to accrete material from its surroundings, the rest-mass energy of infalling material can be converted into radiation or fast particles with greater efficiency than seems achievable by any other process. If the efficiency were ten or twenty per cent, a quasar luminosity of 10^{46} ergs per second would require an accretion rate of between one and two solar masses per year. If the quasar activity has a duration of millions of years, and is able to release the total energy inferred to be present in extended radio sources, a plausible estimate of the central mass required is thus about 10^8 solar masses. A further argument which leads to a mass of this order is the following: one would in general expect that accretion would be inhibited if the luminosity exceeded the value at which radiation pressure yielded a repulsive force able to balance gravity, and this suggests a mass of at least 10^8 solar masses if the steady accretion-powered luminosity is to exceed 10^{46} ergs per second.

THE ASTROPHYSICAL CONTEXT

These arguments are very general ones, and could have been developed by ground-based physicists who had never even looked at the sky. The next step is, therefore, to place these considerations in a realistic astrophysical context, and to enquire how a sufficiently large mass of material might accumulate in the centres of some galaxies. Some of the possibilities are sketched in the flow diagram shown as Figure 2. The main message of this rather complicated diagram is this: once a large enough mass has become concentrated within a sufficiently small region, a runaway process leading to the eventual formation of a massive black hole seems almost unavoidable.

A massive gas cloud might of course collapse right away into a massive black hole. Alternatively the gas cloud might condense into a dense stellar system of the kind that has been discussed over the years by Spitzer and a series of collaborators. Dense star clusters will inevitably evolve to the state where stellar collisions and disruptions become important. Maybe the gaseous débris thereby released will recondense into new stars, but one can show that eventually the luminosity and associated radiation pressure becomes so great that new stars cannot condense. The stars in the cluster will then disrupt or dissolve to form an amorphous supermassive star. Alternatively, of course, a supermassive star might form directly from the gas cloud. Another possibility is that in the dense star cluster, coalescence builds up clusters of hundred-solar-mass stars which, as Colgate has discussed, will give multiple supernovae. This will then leave a cluster of neutron stars or stellar-mass black holes. Time does not permit me to discuss the various possible sequences of events in detail, but the diagram at least gives some indication of the varied paths whereby a galactic nucleus may evolve towards a black hole.

It is clear from this diagram that massive star clusters, massive objects, and accreting black holes, all of which have been proposed by different authors as models for active galactic nuclei, may represent successive stages in the evolution of a single system. Moreover, once a black hole has formed, it is a potentially more efficient power source than any conceivable progenitor. So it seems plausible to interpret quasars, the most powerful cosmic phenomena, in terms of black-hole accretion processes. Some of the precursor stages from which they evolve may yield an explanation of some less spectacular types of activity in galactic nuclei. The required inflow of material could be supplied by gas lost by stars in the body of the galaxy, provided that this material is not swept out by a galactic wind. Alternatively, the gas could be débris from collisions between stars in the nuclear regions, or could even be supplied by stars whose orbits take them so close to the black hole that they are ripped apart by tidal forces.

Production and Expulsion of Relativistic Plasma

There thus seems no inherent implausibility in the idea that massive objects may collapse in galactic nuclei, and that they may thereafter be fed by sufficient material from their surroundings to generate quasar-level luminosities. We must next consider whether this luminosity can be channelled into the characteristic forms that are observed. Quasar radiation is predominantly "non-thermal" in the sense that it consists of low-energy photons produced by energetic relativistic electrons via the synchrotron process. The acceleration of relativistic particles is known to be widespread in cosmic contexts. Such particles reach the Earth as cosmic rays. We know that some processes occur which can accelerate particles to relativistic energies in solar flares, in shock-waves in interplanetary space, in supernova remnants, and in pulsars. But in all these cases (except possibly pulsars) the relativistic particles, though conspicuous in their effects, are heavily outnumbered by the particles of non-relativistic gas in which they are embedded.

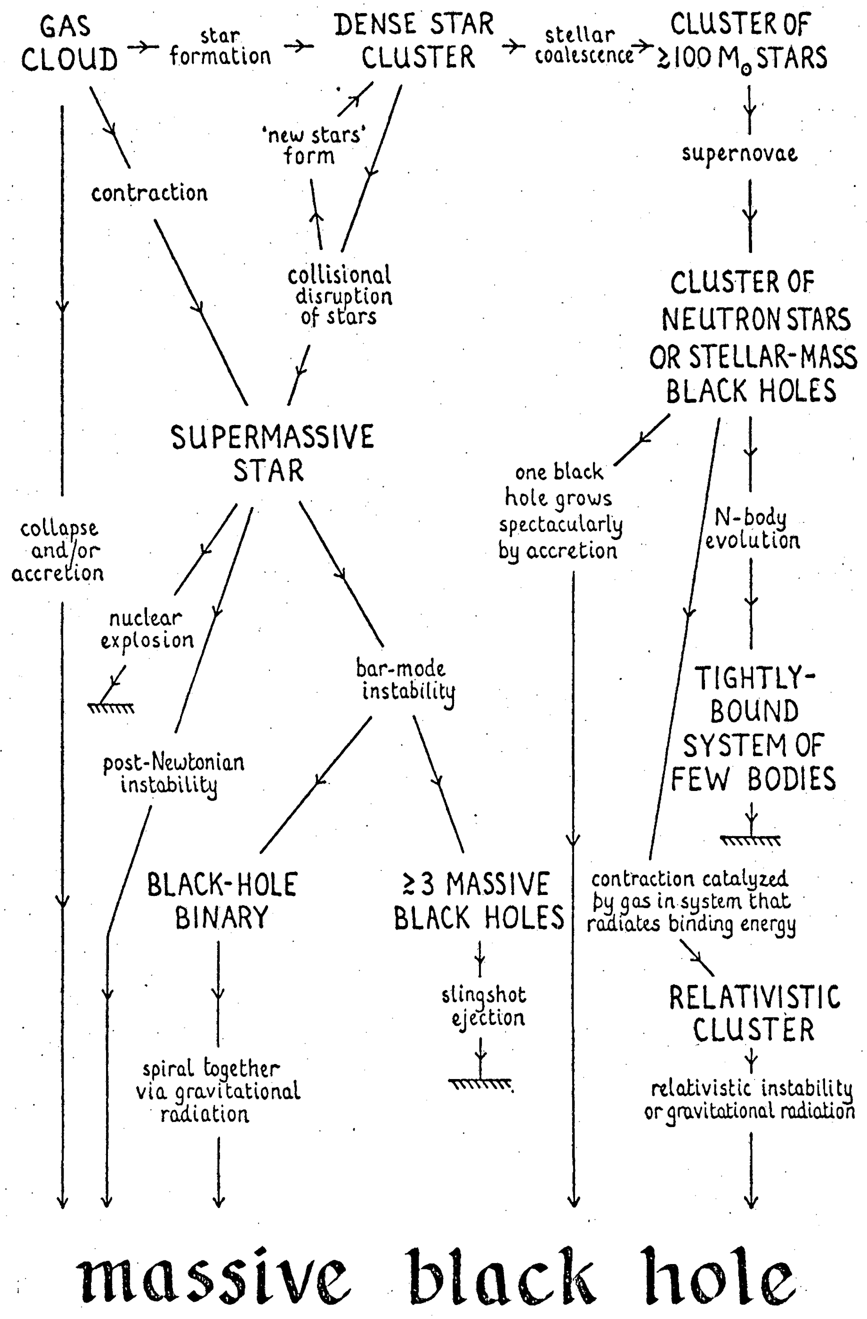

Fig. 2

Possible modes of formation of a massive black hole in a galactic nucleus.

What is remarkable about quasars is that they involve the production of gas in which almost all the electrons are relativistic.

There are several ways in which such gas could be produced in the immediate vicinity of massive black holes. Any gas orbiting near the hole would be moving at a speed comparable with that of light. If two clouds were to collide near the hole, one might then expect the production of a spray of relativistic particles, carrying away much of the relative kinetic energy of the clouds. Another class of possibilities involves analogies with what may be going on in pulsars. An exotic process recently discussed by Blandford and Znajek involves the idea that a magnetic accretion disk around the black hole could induce along the rotation axis electric fields which become strong enough to be shorted out by vacuum breakdown. This breakdown occurs when curvature radiation in strong magnetic fields (or Compton scattering of soft photons) leads to the production of gamma rays, which then transform into electron–positron pairs. These pairs then in turn produce further curvature radiation or scattered photons. For quasar parameters, this mechanism efficiently converts the energy directly into electron–positron pairs with energies of 10^{12} electron volts. This model is an appealing one because the high polarization of non-thermal quasar emission is hard to reconcile with estimates of the expected Faraday rotation due to the relativistic electrons themselves. The presence of equal numbers of positrons yields a zero nett effect. The rapid variability in optical luminosity and polarization in many quasars, and spectacular outbursts like that in AO 0235+164, are perhaps the phenomena which give most direct evidence of conditions and instabilities near the black hole itself.

The extended radio structure of some active galaxies suggests that relativistic plasma generated in the nucleus can in some cases escape to large distances. Does this model then yield any natural interpretation for the ubiquitous directivity and double structure of radio sources? If the central engine were surrounded by a gas cloud, one might imagine that the relativistic plasma would tend to squirt out along the directions of least resistance. If the surrounding material were in a rotationally flattened distribution, these directions would lie along the rotation axis. One can then calculate that the only possible stationary outflow pattern is one in which the relativistic plasma makes for itself a channel whose shape is similar to the well-known "de Laval nozzle" in jet engines. The plasma will then emerge from the galactic nucleus as two collimated beams, as shown in Figure 3. It was suggested some years ago that the lobes of double sources like Cygnus A could be energized by continuously outflowing beams of plasma collimated in the nucleus. Although the arguments for this conjecture were originally indirect, there is now firmer evidence that these beams actually do exist.

The double radio source 3C 236 is the largest such object yet discovered. Its total linear extent is about twenty million light years. There is clear evidence of radio emission from ridges linking the components to the central galaxy. More significantly, there is now evidence that the compact source around the nucleus of the central galaxy is itself extended precisely along the direction of the overall source axis. This indicates continuing activity lasting for tens of millions of years, and also that the collimation direction has remained constant over that time.

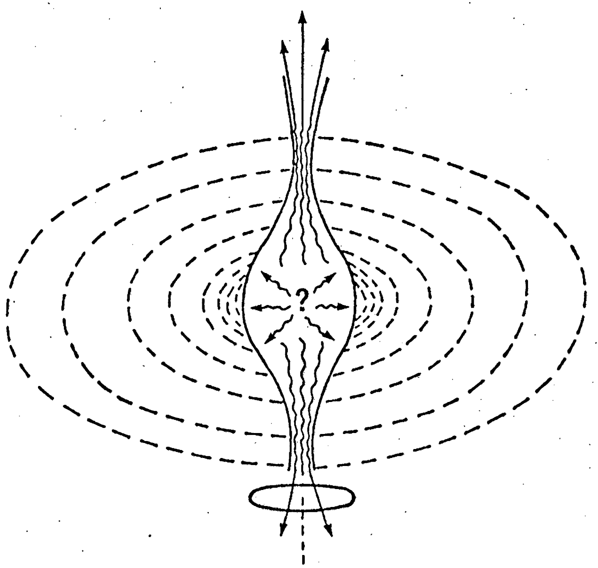

FIG. 3

Production of "twin exhaust" jets when a steady source of relativistic plasma ("?") is surrounded by a rotationally-flattened gas cloud. (After R. D. Blandford & M. J. Rees, *M.N.*, 169, 395, 1974.)

Of even greater interest is the structure of the source associated with NGC 6251. A low-frequency radio survey recently revealed a very extended double source, with very high energy content even though the current radio power output is low. A five-gigahertz map made with higher angular resolution revealed a straight jet, shown in Figure 4, emerging from the galaxy and pointing towards one of the components. Very-long-baseline interferometry measurements have subsequently shown that, right in the nucleus itself, there is a source only a few light years long pointing along the jet. The nucleus of this galaxy thus contains a "cosmic blow-torch", generating a jet detectable out to a distance of half a million light years, and presumably pumping energy continuously into the diffuse extended structure. The fact that the jet is seen only on one side of the galaxy might indicate that it is emerging relativistically; unless the axis is precisely in the plane of the sky, the Doppler effect would strongly enhance the detectability of the jet on the approaching side. (While preparing this lecture, incidentally, I searched for some apposite reference to the work of Halley himself. In this I was completely unsuccessful. I did, however, discover that the first Halley Lecture, given by Henry Wilde in 1910, was entitled "Celestial Ejectamenta". The theme of that Lecture was comets, but these recent radio-source observations suggest that I could have forged an historical link by using the same title for my lecture today!)

DEAD AND DYING QUASARS

The existence of extended structures like 3C 236 sets a firm lower limit of tens of millions of years to the duration of the energy output from active nuclei. Two indirect arguments, however, suggest that the lifetimes are not in fact much longer than this, and certainly not as long as 10^{10} years.

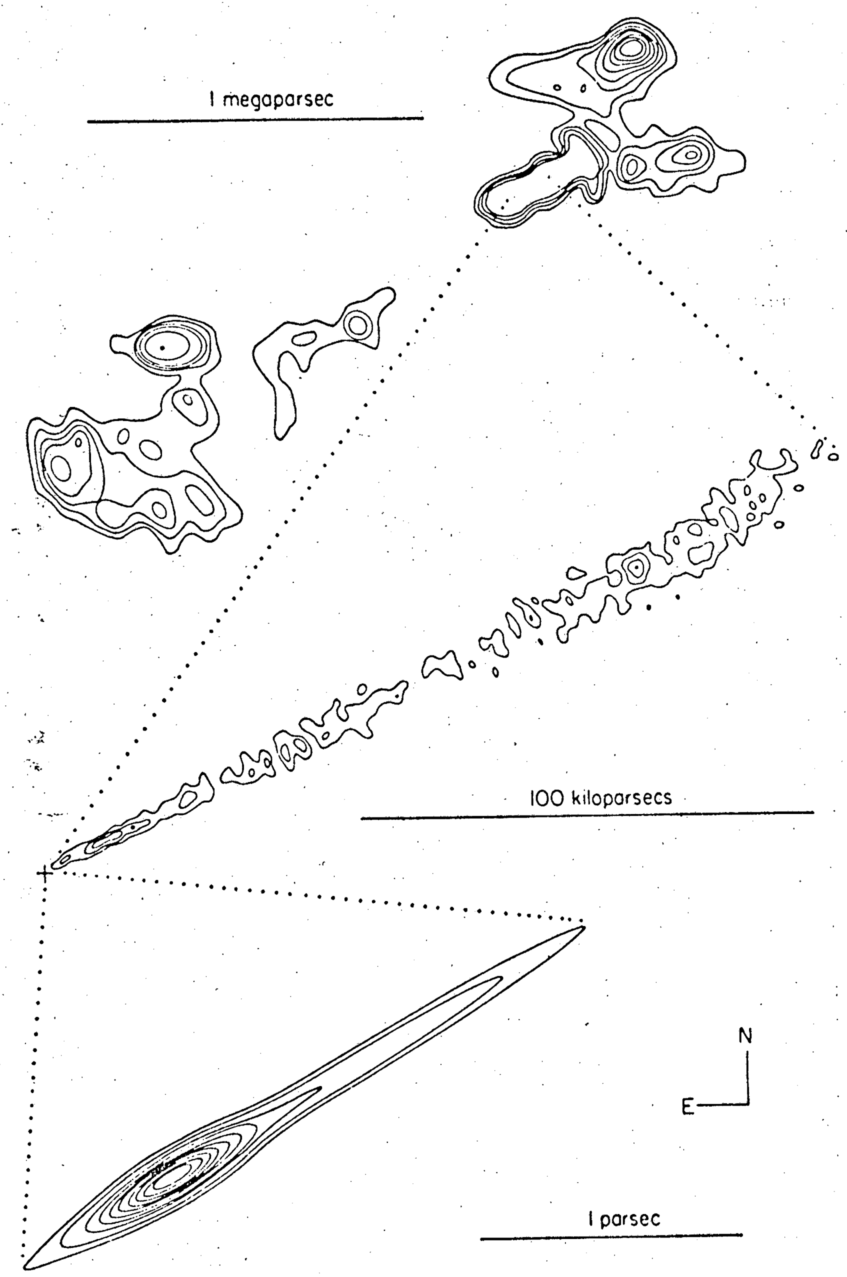

FIG. 4

Radio structure of source associated with NGC 6251 on three different angular resolutions. (From A. C. S. Readhead, M. H. Cohen & R. D. Blandford, *Nature*, **272**, 131, 1978, with permission.)

First, the energy problems would plainly be aggravated if the power continued for such long times. Secondly, as I shall explain, there is evidence that most of the active nuclei which existed in the past have now died out, suggesting an upper limit of 10^9 years. One may thus conclude that dead quasars outnumber the living ones, and that many earlier generations may now be defunct. A dead quasar would presumably be a massive black hole now almost quiescent because it is starved of fuel: starved either because it is in a galaxy that is now swept clean of gas, or because it has already gobbled up all the stars near it. It is therefore interesting to ask whether massive black holes, remnants of dead quasars, may lurk in the nuclei of any well-known nearby galaxies.

Centaurus A, at a distance of about 5 megaparsecs, is the nearest radio galaxy. It has very large radio components which have low power output but which, like NGC 6251, contain relativistic plasma with a total energy of 10^{60} ergs. It can be plausibly interpreted as a very bright radio source on its last legs. Though it has now suffered adiabatic losses and almost faded away, it might in its prime have been a powerful radio source rivalling Cygnus A. One might thus expect a massive black hole to remain as the defunct remnant of what gave rise to this energy. There is now known to be, right at the centre of Centaurus A, a tiny radio source only a light-day across, and an X-ray source emitting 10^{44} ergs per second which is variable on time-scales perhaps as short as hours. These phenomena can be attributed to a slow draining of remaining material onto a black hole whose mass must exceed 10^7 solar masses if it were the progenitor of the radio source. Centaurus A thus may contain the nearest massive black hole still manifesting the effects of accretion.

Slightly farther away, the giant elliptical galaxy M 87 in the Virgo cluster has been known for sixty years to have a peculiar jet emanating from its nucleus. Evidence has recently been put forward that the concentration of stars, and their velocity dispersion, is enhanced within the central few hundred light years. This indicates the presence of an excess dark mass of about five thousand million solar masses. There are several forms which this mass might take, but one obvious possibility is that it might be a single monster black hole. A black hole as large as this has the interesting property that a solar-type star could pass irreversibly within it without having been tidally disrupted. There would thus not necessarily be any conspicuous luminous activity even were it surrounded by a dense stellar system.

Is there any evidence for a massive black hole in the centre of our own Galaxy? There is in fact a very peculiar compact radio source right at our Galactic centre, which is not like any other known kind of radio source: it is not like a pulsar, it is not like a supernova remnant, and is only about 10^{14} centimetres across. It is a unique source in a unique place, and could be attributed to a very low level of accretion onto a massive black hole. On the other hand an upper limit to the permitted mass is set by infrared observations of the neon emission lines from gas near the galactic nucleus. The fact that these velocities are not anomalously high sets an upper limit of five million solar masses. This means that our Galaxy can *never* have been a spectacularly powerful quasar or radio source. Maybe there is a general tendency for the most energetic phenomena to occur in elliptical galaxies, where the angular momentum is lower, rather than in spirals.

In the remaining time, I should like to comment on the more general implications and potential relevance of quasars for gravitation theory, for cosmology and galactic evolution, and for physics generally.

QUASARS AND GRAVITATION THEORY

Gravitation theory is plainly going to be a key ingredient in any satisfactory quasar theory, which is one of the contexts where we cannot get by, as we can in most of astrophysics, with Newtonian gravitation. It is now over sixty years since the general theory of relativity was enunciated. Even though the "expanding Universe" solutions of Einstein's equations were already familiar in the 1930s, the prospects of discriminating between different cosmological theories were then dim. Relativity theory was then regarded as a rather stagnant topic, in glaring contrast with its present status as one of the liveliest frontiers of fundamental research. The renaissance in gravitational physics stems partly from the utilization of new mathematical techniques, but it was also stimulated in the 1960s by the realization that objects where relativistic effects are large may actually exist. In the short run, the most useful tests of gravitation theories may come from high-precision experiments in the solar system. (Already these experiments are precise enough to exclude most rival theories and to confirm general relativity, at least in the so-called post-Newtonian approximation, with a precision of a few per cent.) But to confirm the coefficient in the first term of a power series is not the same as vindicating it in the strong-field limit: to do this one must look further afield, possibly to black holes and to the big bang itself.

Much of what I have said about the inevitability of gravitational collapse is insensitive to the detailed gravitational theory: the argument requires only that gravity should not, for instance, become repulsive in strong fields. The general arguments that accretion provides efficient mechanisms for generating non-thermal power are also qualitatively insensitive to gravitation theory. General relativity does, however, tell us *quantitatively* what black holes are like. One of the key recent theoretical results has been the proof that black holes can form even when the collapse is not spherically symmetrical. Moreover, it seems that once a black hole forms it emits a burst of gravitational radiation, and quickly settles down to a standardized stationary state whose external gravitational field is characterized simply by two parameters, mass and spin. This result is colloquially described as the theorem that "black holes have no hair".

To relativists, galactic nuclei signify the places where the space of our Universe gets punctured by the accumulation and collapse of large masses—collapse to standardized geometrical entities describable exactly by fairly simple equations. It would be exciting indeed if quasar observations led to some crucial diagnostic whereby, for instance, the radiation emitted by gas swirling inward towards a black hole has some measurable characteristic that directly indicates the form of the space–time metric. Optimists may also of course hope that one might eventually detect bursts of gravitational radiation signalling the formation of massive black holes, but this would be feasible only if they formed in a peculiarly sudden way. The arguments in favour of black holes, and the prospect of making detailed relevant observations, seem less clear for quasars than for the putative stellar-mass black holes identified with some X-ray sources, but it is perhaps the more massive holes which hold out the best long-term prospect for confronting observations with gravitation theory. This is because a black hole of stellar mass develops only after collapse to nuclear densities, with all the physical uncertainties entailed by high-density physics; a black hole as massive as the one postulated in M 87 would, on the other hand, have formed before the mean density of its constituent material exceeded that of air. An experimenter falling into such an object would still have several hours, or even days, for leisured observation before being discomfited by tidal forces or imminent incorporation in the singularity.

COSMOLOGY

Any investigations of quasars are bound to impinge on cosmology. If it is accepted that the Universe exploded from an initial big bang, the most basic cosmological question concerns its eventual fate. Will it go on expanding for ever, finally suffering the heat death first discussed by Sir James Jeans? Or will the cosmic recession eventually halt, to be succeeded by a phase in which the galaxies draw closer to each other, displaying blueshifts instead of redshifts, until they eventually collide and coalesce, their constituent stars finally finding the external radiation hotter than their interiors, the contents being finally engulfed in a "big crunch", a Universal fireball like that from which everything apparently emerged? Indirect arguments based on the mean density of material in the Universe seem to be tentatively tilting in favour of an ever-expanding model. Direct measurements of the deceleration by studying the magnitude–redshift relationship of distant galaxies are still disappointingly inconclusive. This is partly, of course, because one has to study galaxies that are very distant, and so inevitably very faint. But even more serious are the various evolutionary corrections which have to be applied, and which are as yet so inadequately quantified that they bedevil the whole procedure.

One might have hoped, and many astronomers initially did, that quasars would greatly aid this task. They are, after all, hyperluminous beacons detectable out to vastly greater distances, thereby enabling us to probe much farther back into the past. But there is again the stumbling block that their evolution is inadequately understood. Moreover, the many statistical studies that can be carried out of the spatial distribution of quasars all indicate that the evolutionary effects are very dramatic: the density of powerful sources would have been about a thousand times higher at early epochs than at the present time. The most distant known quasars are so far away that they emitted the radiation which we now detect when the Universe was less than one quarter of its present age. By observing such objects we are thus in effect probing 80 per cent of cosmic history and investigating an epoch when galaxies were only recently formed, so perhaps the size of the evolutionary effects should not surprise us. A hypothetical astronomer observing the Universe only two thousand million years after the big bang would have perceived a vastly more active and dramatic celestial environment. Whereas our nearest bright quasar, 3C 273, is about two thousand million light-years distant, he would be likely to find a similar object fifty times closer, and appearing as bright as a fourth-magnitude star. Galactic nuclei were much more prone to indulge in active outbursts when they were young.

The study of distant quasars, and attempts to detect even larger redshifts, are thus crucially important for the study of galactic evolution. All the problems are so interrelated that we will not understand the dynamics or kinematics of the cosmos until we have a clearer perception of galactic evolution, and of what happens in active nuclei. Therefore, observations must be pursued on a broad front, in the hope that all issues will gradually clarify concurrently.

PROCEDURES AND PROSPECTS

Now there are some respected researchers on quasars who, if they were here today, would by now be accusing me of blinkered dogmatism: I have spoken within the framework of conventional physics, and interpreted quasar redshifts in terms of the Universal expansion. I would indeed be giving a biased survey if I did not at least recall the long-running controversy over these questions: the claims that anomalies in the redshifts or spatial distribution of quasars indicate that some fundamentally new process is operating; or the assertion that the problems are so intractable that they demand new physics, either a different explanation of redshifts so that quasars can be nearer, or else a more efficient energy-production mechanism.

All who have followed this debate about quasars must have found it fascinating, not only for its intrinsic scientific importance, but also because of the way it has highlighted the contrasting attitudes of different scientific personalities. Many who have supported the conventional view would have been genuinely disturbed if anomalous redshifts really existed, because it would have meant that we were farther from definitive delineation of the Universe's large-scale structure. On the other hand, those who espoused radical or iconoclastic views would have been elated if astronomical observations had upset the apple-cart and revealed some fundamentally new physics, so that astrophysics was more than merely an exercise in applying laboratory physics under extreme conditions. Philosophers of science of the Kuhn school would be surprised at the many astronomers who are eager rather than reluctant to jump on a revolutionary bandwagon.

My own attitude, apparently not widely shared, is that of a *reluctant* conservative. I wish the radicals were right, but am sceptical about the arguments they have advanced, and doubtful that the need for new physics has yet been justified. Many aspects of quasars are indeed problematical, and not much is yet satisfactorily explained. But the same can be said of many better known and better studied phenomena in astrophysics (the solar cycle for instance), and even in terrestrial and laboratory physics. It would be surprising if the puzzles of quasars had been cracked by the limited efforts of the few astrophysicists interested in the subject. So it would seem premature to assert that quasars transcend conventional physics. Progress has been slower than we hoped, but by no means slower than could reasonably have been expected. We have certainly not reached such an impasse as to justify unthinking abandonment of orthodox ideas. Novel and unconventional models would perhaps reveal even more glaring difficulties if made equally specific.

One could argue that quasars were really discovered too early in the development of astrophysics. In 1963 they did indeed seem qualitatively different from anything hitherto known. The associated energy problems did seem to demand some new physics, and many bizarre ideas were proposed. Only later were intermediate phenomena such as Seyfert galaxies seriously investigated. And only later, through the discovery of pulsars and compact X-ray sources, did we recognize the existence of compact objects capable of converting gravitational energy, very efficiently, into non-thermal radiation. These now serve as small-scale prototypes for what might be going on in quasars. Had quasars been discovered in (say) 1973, when these other concepts were already familiar, I would guess that a consensus would have quickly emerged that models involving evolution towards a massive black hole, and subsequent accretion onto it, were an acceptable best buy. This idea was in fact suggested by Zel'dovich and Novikov in 1964, but little work was done to follow up the details. It seems now the most plausible of specific options. The idea may have eventually to be discarded; but even if we think it has less than a fifty-per-cent chance of being vindicated, it is more plausible than any equally specific alternative, and it is thus probably sensible methodology for a theorist to focus on it. Such a policy might be adopted simply through slavery to fashion, but (as Carter has recently argued) it can be justified because the "orthodox" theory of a phenomenon is, almost by definition, the most highly developed of the theories that have not yet been eliminated empirically. Thus, following the orthodox approach is usually the most effective strategy for obtaining a decisive confrontation between theory and observation, in the course of which the current orthodoxy will be either reinforced or else overturned in favour of what then becomes the new orthodoxy.

The phenomena relating to galactic nuclei are bewilderingly varied, and they may not all fit into a single simple coherent picture. The interpretation of the data may involve all the processes indicated in my Figure 2, and indeed many as yet unenvisaged mechanisms. The astrophysicist can hope only to offer at least some ingredients of a valid theory. His task is like that of an engineer, attempting to meet specifications by intelligently combining a set of given components, but with the uneasy feeling that an essential part may still be lacking.

Few astrophysical phenomena, and certainly not quasars, offer the possibility of confronting a simple model with a crucial observational test. Instead, the astrophysicist formulates a general picture, nowadays sometimes termed a "scenario", in terms of which the observer can interpret his data and formulate new programmes. The "scenario" also suggests to the theorists well-posed problems that require further study in order that the "scenario" can be refined or modified. Even to delineate a proper "scenario" demands far more data than are yet available. What we have now is more like a crude caricature than a proper picture, though we may hope that, like a good caricature, it contains (or even highlights) the essential features.

Over the next few years we can expect the accumulation of larger and more systematic bodies of data on quasar samples, which might lead to the discovery of significant correlations. We can also expect more detailed studies of individual objects. Technical advances which will be of great importance include future X-ray telescopes, which may reveal variable X-ray emission coming from the small central regions of quasars, and, in 1983, the improvement in optical resolution and spectral coverage offered by the Space Telescope. The goal is obviously to understand the quasar phenomena to at least the same degree as we can now claim to understand the structure and evolution of ordinary stars. Whereas the latter involve relatively well-understood topics such as atomic and nuclear physics, an understanding of quasars seems certain to involve relativistic gravity and high-energy plasma processes. It may involve something fundamentally new, and should, as a byproduct, clarify our understanding of galaxies and cosmology. At the moment, when even the most basic outlines are conjectural, it would be foolish to expect any quick payoff or any rapid progress towards precise answers. But as our compensation we have the intellectual stimulus of participating in a fascinating on-going interpretative debate, and I hope I have conveyed at least something of its flavour.