# IV

## PRIME MOVERS, MODELS AND MECHANISMS

*"But a clean cut refutation, leading to abandonment of some theory, happens only rarely in astrophysics; many models have persisted unrefuted for a long time. A cynic might argue that they have survived only because they don't go beyond generalities, or else because their proponents have been adept, like the motor mechanics who must abound here in India, at replacing or modifying faulty parts to keep shaky old models 'roadworthy'."*

- Martin Rees (p.7)

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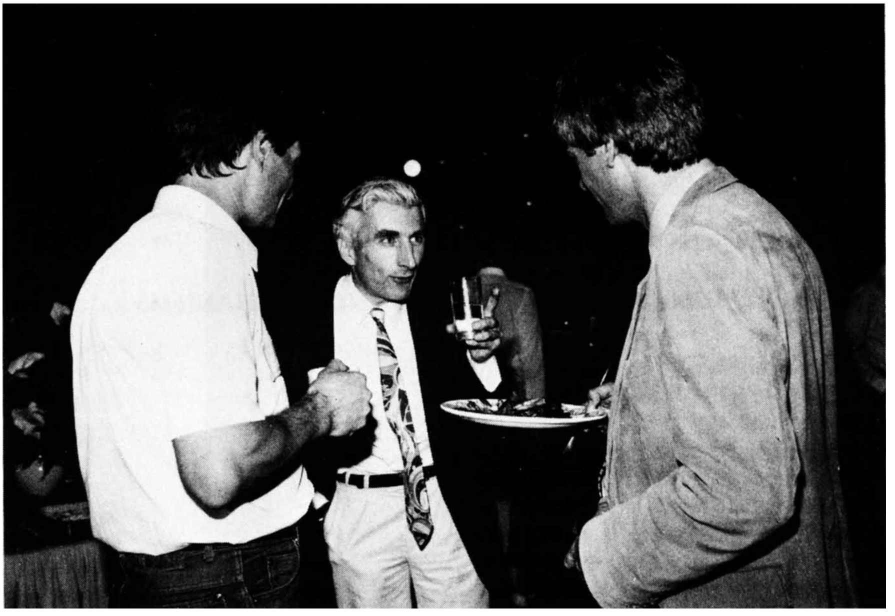

Martin Rees cautioning Roger Blandford about black holes ?

*"The generic black hole model is not infinitely flexible, and not invulnerable."*

- Martin Rees (p.6)

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# BLACK HOLE MODELS OF QUASARS

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ABSTRACT. Observations of active galactic nuclei are interpreted in terms of a theoretical model involving accretion onto a massive black hole. Optical quasars and Seyfert galaxies are associated with holes accreting near the Eddington rate and radio galaxies with sub-critical accretion. It is argued that magnetic fields are largely responsible for extracting energy and angular momentum from black holes and disks. Recent studies of electron-positron pair plasmas and their possible role in establishing the emergent X-ray spectrum are reviewed. The main evolutionary properties of active galactic nuclei can be interpreted in terms of a simple model in which black holes accrete gas at a rate dictated by the rate of gas supply which decreases with cosmic time. It may be worth searching for eclipsing binary black holes in lower power Seyferts.

## 1. INTRODUCTION

As this topic has been extensively discussed in several recent conference proceedings and review articles, (e.g. Phinney 1983, Blandford 1984, Begelman, Blandford, and Rees 1984, Begelman in Miller 1985, and especially Rees 1984), I shall emphasize recent developments. More complete references can be found in the cited articles.

The original idea that quasars contain black holes (Zel'dovich and Novikov 1964, Salpeter 1964, Lynden-Bell 1969) has developed into a fairly strong hypothesis, namely that essentially all galaxies contain massive black holes which power most of the non-stellar activity that we observe in their nuclei.

This hypothesis is motivated by observational and theoretical considerations which include:

(*i*) Rapid variability in several Seyferts and BL Lac objects on timescales that have been reported to be as short as 30s.(Feigelson *et al.* 1985, preprint).

(*ii*) Observations of linear radio features in all types of active nucleus. This suggests the presence of a stable gyroscope like a spinning black hole.



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(*iii*) Dynamical estimates of central masses. In the case of M87, this is $3 \times 10^9\ M_\odot$. Masses of $\sim 10^6\ M_\odot$ have been inferred in the nuclei of M31, M32 (Tonry 1984, Dressler 1984) and a similar mass may be present in our galactic centre. (Crawford *et al.* 1985).

(*iv*) Low level radio and emission line activity in most galactic nuclei (e.g. Keel in Miller 1985). Broad wings to these emission lines are commonplace and have been used to infer the presence of central black holes (Filippenko and Sargent 1985).

(*v*) Superluminal expansion, which suggests the presence of a relativistic gravitational potential well.

(*vi*) Inferred efficiencies of conversion of rest mass energy into radiant energy up to $\sim 10\%$ which suggests that gravitational energy rather than nuclear energy is involved.

(*vii*) Evolutionary arguments which suggest that alternative prime movers like dense star clusters or spinars will soon form black holes.

It hardly needs emphasizing that although this is all good circumstantial evidence, we have no *proof* that black holes exist in active galactic nuclei or indeed anywhere else.

## 2. PROPERTIES OF BLACK HOLES

For the sake of completeness, I will list some key features of massive black holes. For a hole of mass $10^8\, M_8\, M_\odot$, the gravitational radius is $r_g \sim 1.5 \times 10^{13}\, M_8$ cm and the associated time is 500 $M_8$ s. A fiducial power is the Eddington luminosity $L_E \sim 10^{46}\, M_8$ erg s$^{-1}$ at which the repulsion of the radiation balances the gravitational attraction. If the efficiency of conversion of rest mass into energy is $0.1\,\varepsilon_{-1}$ then the associated mass accretion rate is $\dot{M}_E \sim 2\,\varepsilon_{-1}(L/L_E)M_8\, M_\odot\, \mathrm{yr}^{-1}$. If the escaping radiation can be thermalized (i.e. $\tau_{es} \gtrsim 1000$),then the equivalent black body temperature for an effective emitting area $A$ is

$$T_{BB} = 3 \times 10^5\, M_8^{-1/4} \left(\frac{L}{L_E}\right)^{1/4} \left(\frac{A}{100 r_g^2}\right)^{-1/2} \mathrm{K} \tag{1}$$

In a standard thin disk model, $A \gtrsim 100\, r_g^2$ and the flux peaks at a frequency $\sim 3kT_{BB}/h$ which lies in the UV.

In a spinning black holes, described by the Kerr metric, up to 10% (i.e. $\sim 2 \times 10^{61} M_8$erg) of the mass can be extracted by electromagnetic fields supported by exterior currents in the form of a relativistic electromagnetic wind. (Thorne, 1985).

## 3. INTERPRETATION

These basic considerations suggest a qualitative interpretation of the different classes of AGN. Let us suppose that there are three separate channels through which an accreting black hole can radiate; a thermal channel in the UV, a non-thermal channel that produces power law spectra from the far IR to gamma ray energies and a relativistic hydromagnetic channel that is responsible for the jets and the distant double radio sources. We then hypothesise that

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the branching ratios for these three channels are mainly determined by the ratio of the mass supply rate to the critical accretion rate. When this ratio is large, we expect an accretion disk to form that is both geometrically and optically thick. A large fraction of the power will be released through the thermal channel at about the Eddington limit. However the gas flow near the black hole is unlikely to be steady and a substantial power will probably also be released through the non-thermal channel via shocks, flares electromagnetic cascades etc. We identify this case with the radio-quiet quasars (when $M_8 \gtrsim 0.1$) and the Seyfert galaxies (when $M_8 \lesssim 0.1$). By contrast, when the accretion rate is low relative to the mass of the hole, the accreting gas is optically thin and the power is dominated by the hydromagnetic extraction of energy from the spinning hole. This gives rise to a radio galaxy. Quasars associated with extended radio sources occur when the accretion rate changes from being low to critical.

Our classification of an AGN is also influenced by our orientation. Many of the properties of compact radio sources can be accounted for if they are relativistically beamed in our direction (c.f. Saikia, this volume). Similarly, the observed differences between Seyfert 1 and Seyfert 2 galaxies, principally the absence of broadlines and powerful x-ray emission from the latter, can interpreted as the result of absorption by a thick, equatorial disk (e.g. Osterbrock in Miller 1985).

Lower power LINERS, emission line galaxies etc can be associated with low mass black holes, or in some instances intermediate mass holes that are accreting sub-critically but have lost their spin energy in an earlier incarnation as a radio source. The marked preference of extended radio sources for elliptical galaxies and of Seyfert nuclei for spirals can be understood as a reflection upon the likely history of the gas supply.

## 4. STABILITY OF RADIATION TORI

Equilibrium models of thick accretion disks or radiation tori have been invoked to explain radio-quiet quasars and type 1 Seyferts. In most instances, these models adopt a polytropic equation of state and specify arbitrary angular momentum distributions (commonly that the angular velocity $\Omega$ varies with cylindrical radius $r$, or its relativistic counterpart, according to $\Omega \propto r^{-q}$). They do not treat the internal circulation and heat transport self-consistently and, perhaps partly for this reason, they are radiatively inefficient when the mass accretion rate is high, $\dot{M} \gg \dot{M}_E$.

In an important development, Papaloizou and Pringle (1984, 1985) have shown that orbiting tori are susceptible to global, non-axisymmetric, dynamical instabilities. The physical character of these instabilities has recently been elucidated in the case of slender tori (Goldreich, Goodman, and Narayan 1985, preprint, Blaes and Glatzel, 1985, preprint). It now appears that the unstable modes can be interpreted as edge waves that are coupled around an unstable region around corotation. For, modes in which the azimuthal wavelength is long compared with the minor radius of the torus, rapid growth in a few orbital periods is found as long as $\sqrt{3}<q<2$. When $1.5<q<\sqrt{3}$, there are modes with azimuthal wavelength shorter than the minor radius which grow more slowly and may provide an effective viscosity for the inflowing gas. 3D numerical simulations will be necessary to understand the non-linear evolution of these instabilities. (The existence of radio jets assures us that dynamically unstable flows need not be catastrophically disrupted.)

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## 5. MAGNETIC EXTRACTION OF ENERGY FROM DISKS AND BLACK HOLES

Several arguments suggest that magnetic fields mediate nuclear activity.

(*i*) Radio jets frequently appear to have minimum internal equipartition pressures that exceed the maximum permissible external thermal pressure allowed by X-ray observations. This suggests that the pinching action of toroidal magnetic fields amplifies the gas pressure and confines the jets. The current that supports this toroidal field presumably flows along the jet and is believed to be generated by a rotation-induced e.m.f. near where the jet is collimated.

(*ii*) Recent observations of the galactic center (e.g., Morris and Yusef-Zadeh 1986, Sofue and Handa, 1984) exhibit straight "filaments" and "threads", (presumably magnetic flux tubes) extending perpendicular to the galactic plane and appearing to twist. (The sense of twist of the field lines should reflect that of the differential rotation in the underlying disk and should oppose the general galactic rotation.)

(*iii*) Magnetic fields allow the angular momentum that must be liberated by the inwardly spiralling gas to be carried off (e.g., Pudritz and Norman 1983). If the distribution of mass within a galactic nucleus is generally axisymmetric, then there is no efficient way to extract the angular momentum using gravitational forces. This is in contrast to an accretion disk in a binary system. (A non-axisymmetric bar may however be effective.)

(*iv*) Variability data suggests that the non-thermal continuum originates from a highly compact region of high radiation energy density. Relativistic electrons lose energy by Compton scattering on timescales short compared with the crossing time. They must therefore be re-accelerated locally in a highly efficient manner. Electrostatic acceleration associated with rapidly changing magnetic fields, such as might be found in the corona of a differentially rotating disk, is probably the most efficient way of doing this (e.g., Burbidge and Burbidge 1967). The equipartition field strength near the inner edge of an accretion disk is envisaged to be $\sim 10^4$G. The associated electric fields induced by the differential rotation are $\sim 1\mathrm{MVcm}^{-1}$ and strong enough to accelerate $\sim$100GeV electrons.

Arguments like this, developed at slightly greater length in Coroniti(1985) and Blandford in Mihalas and Winkler (1986), suggest that magnetic fields are an important feature of accretion disks and that most astrophysical jets are launched and collimated hydromagnetically. Serious axisymmetric numerical compilations are only just starting to be made (e.g., Uchida and Shibata 1984), but we can anticipate steady progress in this area over the next few years.

## 6. ELECTRON-POSITRON PLASMAS

There have been several recent studies of non-thermal pair plasmas in galactic nuclei (cf. Novikov this volume and an excellent review by Svennson in Mihalas and Winkler 1986). These studies are partly motivated by observations of radio sources. However, the most compelling argument for the existence of pair plasmas within AGN's is that the X-ray spectra in type I Seyferts and radio loud quasars (Elvis, these proceedings) have spectral indices in the range $0.5 \lesssim \alpha \lesssim 1$. If we extrapolate these spectra into the gamma-ray region, ($\varepsilon_\gamma \gtrsim 0.5$ MeV) and use the observed X-ray variability time scale $t_{var}$ as an indication of the source size $R \sim ct_{var}$, then the inferred $\gamma$-ray compactness parameter

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$$l_\gamma = \frac{L_\gamma(\varepsilon_\gamma \geq m_e c^2)\sigma_T}{R m_e c^3} \tag{2}$$

$$\simeq 4\pi \left(\frac{L_\gamma}{L_E}\right)\left(\frac{m_p}{m_e}\right)\left(\frac{r_g}{R}\right) \tag{3}$$

typically exceeds unity (Barr and Mushotzky 1986 preprint). This implies that the optical depth to pair production in the source region ($\gamma + \gamma \rightarrow e^+ + e^-$) exceeds unity and a Thomson-thick pair plasma must be produced. (This extrapolation need not apply to the emergent $\gamma$-rays because which may be absorbed.) The optical - X-ray continua can also be re-processed by Compton scattering by the pair plasma.

Fabian, Guilbert, Phinney, Cuellar, and I have been calculated some simple models of pair plasma in source regions and find that various features of the observed spectra can be reproduced. Although our calculations are of more general applicability, we envisage that gamma rays are created when relativistic electrons inverse Compton scatter thermal UV photons in a corona above the innermost parts of a disk accreting at a near critical rate. We have developed a time-dependent code that evolves the electron and photon distribution functions in such a way as to conserve particle number and energy explicitly. This has enabled us to determine the dependence of the emergent radiation spectrum on the nature of the photon and electron spectra and to explore the time-dependent response to changes in the particle acceleration rate. We find that our results are most sensitive to the treatment of the radiative transfer and that this sets the necessary level of sophistication required to treat the various microphysical processes. The simplest treatment of the radiative transfer is to give every photon an escape probability $c\,\Delta t / R(1 + \tau_c)$ in a time step $\Delta t$, where $\tau_c(\varepsilon)$ is the relevant Compton scattering optical depth (using a simple approximation to the the Klein-Nishina cross section. The microphysical processes that have to be included are inverse Compton scattering by the relativistic electrons, photon-photon pair production, electron-positron annihilation and Comptonisation by the thermal electrons (Fig. 1). Under the conditions of immediate interest, the electrons and positrons cool to non-relativistic energies through inverse Compton scattering before there is any significant annihilation. In a steady state, the Thomson depth is then a direct measure of the total production rate of relativistic pairs.

Two limiting cases can be handled analytically. When secondary pair production is ignorable and electrons are injected mono-energetically with energy $\gamma = \gamma_{max}$, inverse Compton cooling establishes a steady state electron distribution function $N_\gamma \propto \gamma^{-2}$ for $\gamma < \gamma_{max}$. The X-ray spectrum of the inverse Compton scattered ultra-violet photons therefore has a spectral index $\alpha = 0.5$. In the opposite limit, when secondary pair production dominates the steady electron spectrum, $\alpha = 1$.

We find that when we include the reprocessing by the thermal electrons, the observed X-rays spectral index has an intermediate value $0.7 \lesssim \alpha \lesssim 0.9$ for a substantial range of soft photons to relativistic electron power ratios (0.1 - 1.0) and compactness parameters $1 \lesssim l_\gamma \lesssim 100$. More compact sources have steeper X-ray spectra and this may possibly be related to the observations of radio-quiet quasars (Elvis, this volume). The emergent flux above $\sim 100$ keV is generally much smaller than given by an extrapolation of the X-ray spectrum an account of Compton recoil on the cool thermal electrons and the high pair production

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opacity. An annihilation line is also generally present, although it must be borne in mind that dynamical expansion of the source region will probably smear it out.

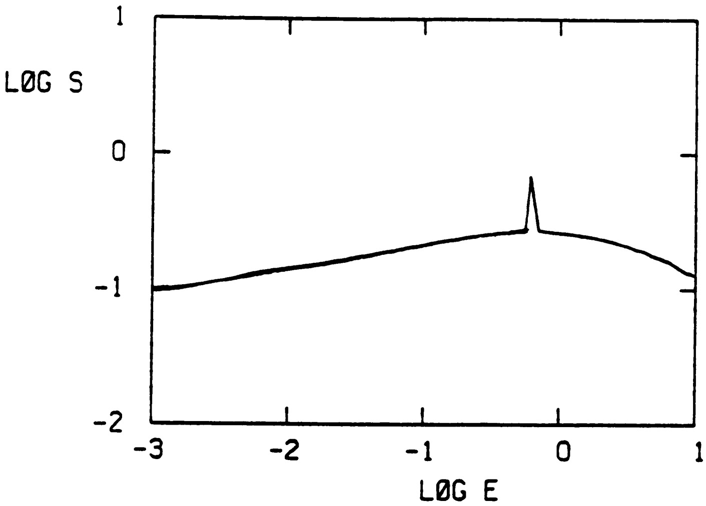


Figure 1. Stationary X-ray and $\gamma$-ray spectrum from an electron-positron plasma. Soft photons are injected with a compactness parameter (see text) of 1 and 500 MeV electrons are also injected with a similar compactness parameter. $S$ measures the power per logarithmic frequency interval of the emergent radiation at energy $E$MeV. Note the slope ~0.2 corresponding to a spectral index $\alpha$~0.8 in the 2-10 keV electron range and the 0.5 MeV annihilation line.

## 7. A SIMPLE EVOLUTIONARY MODEL

Much effort has been devoted to inferring the evolutionary properties of AGN purely from the observations. It is generally agreed that powerful radio sources and quasars were far denser (per unit comoving volume) in the past and that weaker sources evolved far less. There has been a parallel effort to try to unify the different types of AGN and to distinguish them by hole mass, accretion rate, orientation, spin, galactic environment, etc. Most of these unifying schemes contain, at least implicitly, an assumption that an individual nucleus can transform from one type to another and so they should predict the evolutionary behavior. This more physically based approach to evolution has been pioneered by Cavaliere, Giallongo, and Vagnetti (1985, preprint). Here, I develop a simple model that is appropriate to the particular unification scheme that I outlined above and which, in contrast to the models of Cavaliere et al. has active galaxies becoming systematically brighter with time.

We make the following simple assumptions.

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(*i*) Essentially all galaxies of moderate or greater mass grow black holes in their nuclei starting from initial masses $M_i \sim 10^3 M_\odot$. These grow at a rate dictated by the local supply of gas which is supplied in fairly large parcels independent of the mass of the hole. The average rate of supply of gas in this form declines with cosmic time $t$ at a prescribed rate $\langle \dot{M} \rangle(t)$.

(*ii*) This gas is accreted by the hole at a critical rate ($\dot{M} = M/t_E \sim M_8 M_\odot \mathrm{yr}^{-1}$, corresponding to a radiative efficiency of 0.1 and a total power of half the Eddington value. The radiation pressure of the escaping photons prevents accretion at a faster rate, although physically, this need not be the case.

(*iii*) Holes that are currently accreting (at the critical rate) are identified with quasars and bright Seyferts whose luminosity depends upon the hole's mass.

(*iv*) Dormant holes, in which the accretion is subcritical are identified with low luminosity Seyferts, LINERS, starburst galaxies and, in the case of large holes in ellipticals, radio galaxies.

We must specify two functions, the galaxy (and hence by assumption) the black hole birth rate as a function of cosmic time ($S(t)$, and the mean fuelling rate ($\langle \dot{M} \rangle$). Given these assumptions, we find that the fraction of holes of mass $M$ that are active at any time is given by

$$\delta(t) = \min[1, \langle \dot{M} \rangle t_E / M] \qquad (4)$$

In other words, holes accrete continuously until the mean rate of gas supply falls below the Eddington rate, whereafter a decreasing fraction of them are observed as bright AGN's. (In fact equation(4) is somewhat inaccurate because it ignores the reservoir of gas whose build up depends upon the history of the accretion. However, as the critical rate of gas supply rises exponentially with time and $\langle \dot{M} \rangle$ declines rapidly, this turns out to be a good approximation.) We now change the independent variable to $L$, the bolometric luminosity of the hole when it is accreting. If the fraction of all galaxies with associated luminosity $L$ lying in unit interval of $d\ln L$ is denoted by $Y(L)$, then $Y(L)$ satisfies the partial differential equation

$$\frac{1}{\delta}\frac{\partial Y}{\partial t} + \frac{1}{t_E}\frac{\partial Y}{\partial \ln L} = S\delta(L - L_i) \qquad (5)$$

where $L_i$ is the critical luminosity corresponding to $M_i$. Equation(5) is straightforward to solve given $S(t)$ and $\langle \dot{M} \rangle$ and it turns out to be possible to choose these functions so that the evolution of the luminosity function over the redshift range $0 < z \lesssim 4$ is qualitatively consistent with what we observe. (See Fig. 2.)

Of course this prescription is overly simple ignoring as it does fluctuations and additional factors, listed above. Furthermore there is no particularly good reason for choosing the birth and fuelling rates that we have used. Nevertheless, the solution does demonstrate that it is possible to account for the principal features of apparent AGN evolution in a fairly natural manner. Some aspects of this solution with observational ramifications should be noted.

(*i*) Most bright galaxies should contain holes with $M \gtrsim 10^8 M_\odot$. In addition most spirals should have been Seyferts for a few percent of their life.

(*ii*) The co-moving density of low luminosity AGN's does not evolve rapidly with redshift; indeed it declines beyond $z \sim 2$. We know that this is probably the case; otherwise the X-ray emission from Seyfert 1 galaxies would exceed the observed X-ray background.

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(*iii*) The co-moving density of intermediate power AGN's also declines beyond $z \sim 3$. This may be related to the apparent lack of quasars in high redshift surveys discussed by Osmer in these proceedings.

(*iv*) The differential evolution of radio sources can also be interpreted in terms of this model if we further assume that the total power of a radio source is roughly proportional to the reducible mass of the central black hole which will spin down on a timescale $\sim 10^9$yr unless reactivated by a fresh period of accretion. Most of the massive holes that are responsible for the most luminous radio sources stopped accreting by $z \sim 2$ and were braked by magnetic torques soon afterwards.

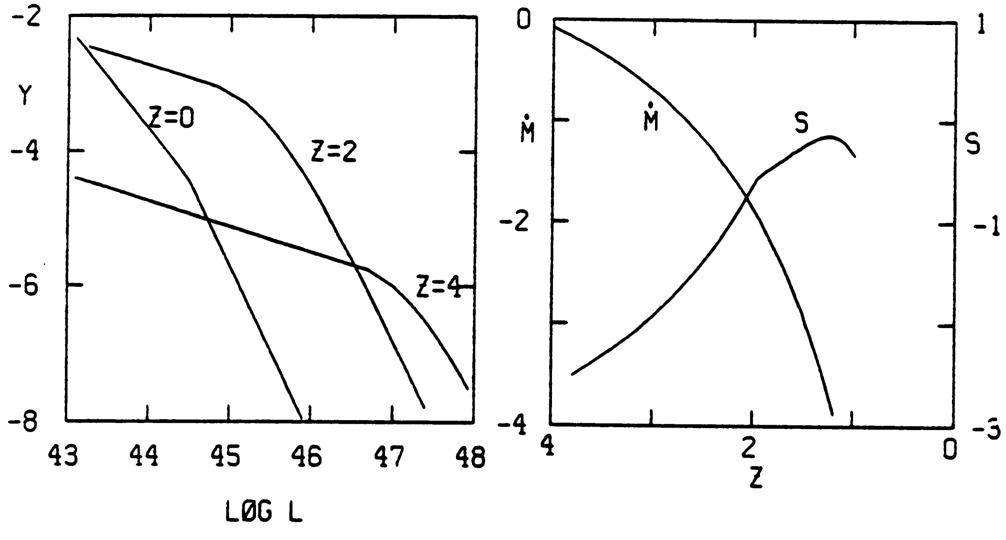


Figure 2. Differential luminosity function ($Y$) for power $L$ erg s$^{-1}$ (plotted logarithmically) at redshifts $z$ = 0,2,4 and associated galaxy birth rate $S$ and mean fuelling rate ($\dot{M}$ M$_{\odot}$yr$^{-1}$) also plotted logarithmically.

## 8. OBSERVATIONS OF BLACK HOLES IN AGN'S

Independent of these higher order considerations, the basic black hole hypothesis is still without satisfactory observational verification. The most immediate hope for changing this lies with space telescope which should be able to perform spectroscopy on the innermost ~10pc of nearby galaxies and thereby determine their central masses dynamically. Further indirect evidence may be forthcoming from GRO if radio sources turn out to be detectable gamma ray sources.

However, the most persuasive evidence would probably be the detection of a black hole binary. As pointed out by Begelman, Blandford and Rees (1980), when two galaxies (each with black holes in their nuclei) merge, the hole associated with the smaller galaxy will sink into the nucleus of the larger galaxy in a few

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orbital periods. Thereafter, the dynamical evolution time will increase to a value $\gtrsim 10^9$ yr until gravitational radiation by the black hole binary takes over. Now, the lifetime in years of a binary comprising holes of masses $10^8 M_{18} M_\odot$ and $10^8 M_{28} M_\odot$ with orbital period $P$ yr is $T \sim 4\times10^7 P^{8/3} M_{18}^{-2/3} M_{28}^{-1}$, where for simplicity, we have assumed that $M_2 \lesssim M_1/3$. Now, contrary to the assertion of Gaskell(1983), it is not very likely that we observe black holes as spectroscopic binaries because the radius of the broad emission line region is typically larger than the radius of the orbit. However, if the black holes are endowed with accretion disks, then there is good chance that they will appear as an eclipsing binaries. We have argued that most galaxies have $\sim 10^8 M_\odot$ black holes in their nuclei and that they are currently active for $\sim 3\times10^8$yr. Suppose that there are $N$ mergers per galaxy and that an eclipsing binary can be recognised if its period is shorter than a year. Then the probability that an individual black hole nucleus harbor an observable binary is the joint probability that $P \lesssim 1$yr i.e. $\sim 10^{-10} TN$ and the probability that it be currently active $\sim 0.03$. If these two probabilities are independent, then a sample of $\sim 10^4/N$ active galaxies must be searched to find one example. However if, as is more likely, binaries are always quite active then they may be up to 30 times more common. Of course this estimate is quite speculative, but it does suggest that a monitoring program of the optical continua of nearby Seyfert and LINER nuclei could be fruitful.

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DISCUSSION

**Burbidge** : There is an old problem concerned with the origin of the rather strong magnetic fields in the extended lobes of radio galaxies. In your theory does the field energy and flux come from the nucleus or is it already present in the intergalactic medium ?

**Blandford :** I believe that the flux is supplied by the nucleus through the jet. Note that the ordered field component along the jet is irrelevant because if flux is conserved, $B \propto A^{-1}$, (A is the area), pressure $\propto A^{-2}$. Fixing the nuclear pressure at a plausible value gives a negligible parallel field in the outer jets and radio lobes. However toroidal field will vary as $B \propto A^{-1/2}$ and is consistent with observed equipartition values. Small velocity gradients across the jet will in addition produce reversing parallel field which may dominate.

**Elvis :** There is a tight connection between IR and X-ray continua in AGN (Malkan 1984, Fabbiano et.al., this meeting), probably tighter than the UV-X-ray correlation. The infrared does not appear in your sketch of a 'Cauldron' spectron. How can you fit this observation into the Cauldron model ?

**Blandford :** I have always been worried by this connection because the IR and X-ray spectral indices are different. However if we accept it at face value then the energy at $\sim 2$ keV may be optimal for seeing an underlying power law, being too high to be contaminated with "thermal" photons associated with the "big bump" and too low to be strongly influenced by the X-rays inverse Compton scattered by the secondary, relativistic pairs. The underlying IR-X-ray power law is most naturally interpreted in this type of model as syncrotron radiation that has been Comptonised by the non-relativistic pair plasma.

**Vinod Krishan :** (1) Could you specify the electromagnetic fields which change into electric field to accelerate electrons ? (2) There is an

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equivalent process to Compton scattering wherein the soft photon is converted to hard photon by the collective behaviour (plasma wave) of the hard electrons, called Raman scattering which is much faster and more efficient. Why are we not talking about it ? (3) If we can accelerate electrons continuously or in situ and get around the problem of life time of electrons we can also solve the problem of life time of plasma waves in the same manner.

**Blandford :** (1) Stationary magnetic fields frozen into an orbiting condensation (e.g. an accretion disk) induce a large EMF and the electric field will occur in regions of higher effective resistance. Changing magnetic fields from shearing flux loops in the disk also produce large inductive electric fields.

(2) I agree that this process may be important under the conditions that you specify.

**Sturrock :** Surely the question of the confinement of a jet by a self-produced magnetic field is not as simple as you suggest. We know from the virial theorem that, from a global view point, the self-produced magnetic field of a plasmoid will always act in the sense of causing expansion rather than contraction.

**Blandford :** Yes, that's correct but not relevant if the jet is surrounded by thermal gas at a lower pressure ($p_g$) than that inside the jet ($p_j$). To give a simple example, suppose that a current I flows axisymmetrically along the walls of the jet, then the toroidal field outside the jet will be given by $B_\phi = 2I/r$. Static equilibrium requires that the jet radius $r_j$ equal $(2\pi p_j)^{-1/2}$ I. There must be a return current however. Suppose that this all flows at the radius $r_g$ where the gas pressure balances the outwardly directed magnetic stress. In this case, $(p_j/p_g) = (r_g/r_j)^2$ . This simple example shows a hydromagnetic equilibrium can be established without violating the virial theorem. As we generally only need to amplify the gas pressure by factors $\lesssim 100$, values of $r_g \lesssim 10\, r_j$ should be adequate.

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*"And one of the few opinions about quasars where the consensus has been steady since 1963 is that the energy is gravitational in origin. (An un-weighted majority view is in itself, however, worth little in this subject ! "*

- Martin Rees (p.4)

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