PHYSICS OF THE CENTRAL ENGINE

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ABSTRACT. I discuss physical processes which may be important in the central engines of AGNs. Black hole accretion models have been elaborated during the past few years, and provide a plausible framework for jet and spectrum formation. However, the specific mechanisms responsible for producing the observed continuum radiation remain uncertain. I consider nonthermal models for the IR continuum, constraints on thermal plasma, and the production of relativistic electrons.

1. INTRODUCTION

By "central engine" I mean the region of an AGN where most of the continuum radiation is produced and where outflows (jets) are initially accelerated. In the context of black hole models described below, this is expected to be the inner ~ 100 R_g ~ 10^{15} M_8 cm surrounding the black hole, where M_8 is the black hole mass in units of 10^8 $M_\odot$. Observations of rapid X-ray and UV variability in some objects support the existence of such a compact central engine, which is much smaller than either the broad emission-line region or the scales (typically ~1 pc) on which jets are resolved by VLBI (Fig. 1).

The physical processes we ascribe to the central engine depend on its morphology, about which we have little information. Are the X-rays produced in an incipient jet, in the corona of an accretion disk, or in a quasi-spherical flow? Does the UV bump consist of radiation generated by viscous processes in a thin accretion disk, or is it radiation reprocessed by optically thick clouds embedded in the X-ray emitting gas (Guilbert and Rees 1988; Ferland and Rees 1988)? While some possibilities may be ruled out by indirect arguments, direct morphological information will not be available until we can make observations with resolution $\lesssim 10^{-4}$ arcsecond at wavelengths shortward of the far infrared. At sub-millimeter and radio wavelengths, luminous AGNs are self-absorbed on scales $\lesssim 10^{17}$ cm. Thus there is an insurmountable physical barrier to direct imaging of AGN central engines

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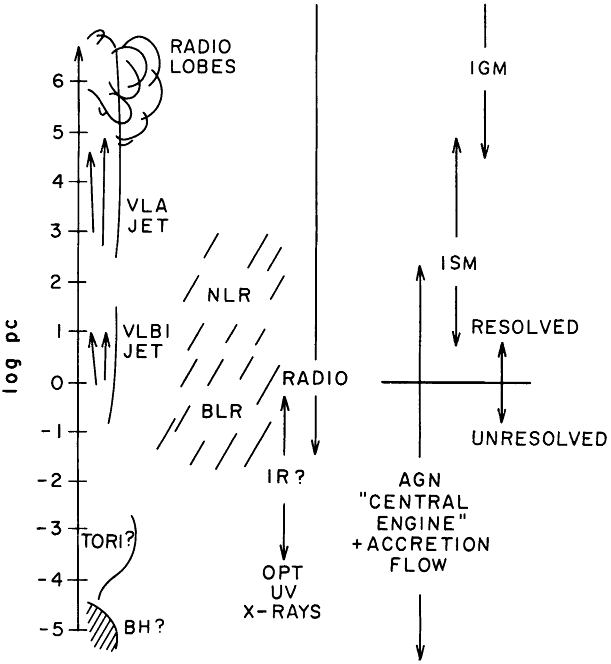

Fig. 1. Scales of major structural features in AGNs.

in the near future, except perhaps for a few nearby, low luminosity objects such as the Galactic Center and NGC 1275 (Bartel _et al._ 1988).

2. THE BLACK HOLE HYPOTHESIS

2.1. Black hole as "prime mover"

A number of arguments support the hypothesis that supermassive black holes are the "prime movers" in AGNs. These may be summarized as follows [see also reviews by Begelman, Blandford and Rees (1984) and by Rees (1984)].

The most direct arguments couple upper limits on the size of the central engine, obtained from variability, with lower limits on its mass. Using variability to estimate size is valid provided that relativistic beaming is not important; thus, the method is questionable for blazars. There are at least three methods of estimating the minimum mass of the central engine: 1) multiply the observed luminosity by a source lifetime, estimated from statistical arguments; 2) use the minimum energy content of relativistic electrons and magnetic fields in radio lobes to estimate the lifetime energy output of the nucleus; 3) compare the observed luminosity to the Eddington limit. The first two methods require one to assume a maximum mass-to-energy conversion efficiency (typically taken to be ~10%), while the first and third methods are subject to uncertainties about the role of beaming. Values of M_{min}/R_{max} typically $\gtrsim 10^{-3}\ c^2/G$ make the presence of a black hole plausible but not incontrovertible. More circumstantial arguments include detections of "dark" masses in the centers of several galaxies (see Dressler, this volume); evidence of relativistic motion in radio jets; evidence of stable jet axes over time scales $\gtrsim 10^6$ years, indicating a good "gyroscope" (a spinning black hole?) at the center; and the "inevitability" of black hole formation through evolutionary processes in the galactic nucleus (Rees 1984).

If one adopts the black hole hypothesis, then the central question of AGN theory becomes: How does the interaction of a supermassive black hole with ambient matter lead to the various manifestations of AGN phenomena? The desired theory must explain the production of both the continuum radiation and jets. Complications become apparent even at the level of very simple questions about the main ingredients of such a theory:

What is the source of the energy? We now know that energy can be released both by tapping the gravitational potential energy of material falling into the black hole (accretion) and by tapping the rotational kinetic energy of the black hole itself (the flywheel mechanism: Phinney 1981). In the most plausible realization of the flywheel mechanism, the region surrounding the black hole must be threaded by magnetic fields generated by currents in the surrounding plasma (Blandford and Znajek 1977; MacDonald and Thorne 1982). This situation would probably lead to significant amounts of energy being released by both mechanisms simultaneously (Rees et al. 1982).

How is the energy released? Angular momentum transport in accreting gas is usually assumed to occur as a result of local viscous processes, which generate heat and ultimately (if the density is high enough) radiation (Pringle 1981). However, not all gravitational binding energy need be released in this way. Blandford and Payne (1982) demonstrated that organized magnetic fields are efficient at removing the angular momentum of an accretion disk. The excess angular momentum and energy of the accreting gas are carried away in the kinetic energy and Poynting flux of a hydromagnetic wind. Energy released by the flywheel mechanism is likely to emerge in similar forms (Phinney 1983). This is good news, because hydromagnetic winds are a promising mechanism for jet production. (Indeed, such winds tend to be self-collimating; Sakurai 1985.) It does, however, lead to additional theoretical complications because kinetic energy and radiation are easily interconverted: e.g., radiation pressure can increase the kinetic energy of an outflow, while radiation drag can convert kinetic energy into an enhanced radiation flux, particularly for relativistic outflows (Begelman and Sikora 1987; Melia and Königl 1988).

How is the radiation apportioned between thermal and nonthermal forms? There are features in AGN continuum spectra which are readily explained as thermal, e.g., the UV bump. We cannot prove that any feature in the AGN spectrum is nonthermal, but much effort has gone into developing nonthermal models for the X-ray and IR continua. If either or both portions of the continuum are nonthermal, we must explain how such a large fraction of the energy going into radiation is channeled through a nonthermal distribution of electrons.

2.2 Accretion onto black holes

In the standard accretion theory it is assumed that the gravitational binding energy released by inflow is transferred to internal energy through local dissipative processes. The structure of the accretion flow (which is likely to have a significant amount of rotational support) depends on whether the internal energy is converted efficiently into radiation, and whether the radiation escapes or not. There are three principal "modes" of accretion, which are outlined below and described in greater detail in the review by Begelman (1985). If the accreting gas radiates efficiently and most of this radiation escapes, then the flow will be a thin accretion disk. When the luminosity approaches the Eddington limit, radiation pressure builds up inside the flow, inflating it into a radiation torus. In this case radiation is produced efficiently but it is prevented from escaping by the large optical depth. An ion torus develops when the density is so low that the hot gas is unable to radiate efficiently, resulting in the buildup of thermal ion pressure (Rees et al. 1982). Gas in an ion torus tends to heat to the local virial temperature, which exceeds the rest mass energy of an electron at $R < 2000\ R_g$. Since relativistic electrons cool very efficiently, ion tori can exist only if the ions can be maintained at a temperature much higher than that of the electrons. The minimal thermal coupling between ions and electrons is through Coulomb collisions, although collective plasma effects may couple the species more rapidly (Begelman and Chiueh 1988). By its nature, an ion torus need radiate only a small fraction of the gravitational energy released through accretion. For this reason it was proposed as the dominant type of flow in powerful radio galaxies, which seem to have kinetic energy outputs far greater than their luminosities (Rees et al. 1982). Thin disks and radiation tori are expected to be luminous in the UV and soft X-rays, and are natural candidates for producing the UV bump.

The three modes of accretion can be classified according to the dimensionless ratio of the accretion rate to the "Eddington accretion rate," $\dot{m} \equiv \dot{M}/\dot{M}_E = \dot{M}c^2/L_E$. A thin disk and an ion torus are both possible at low accretion rates, the thin disk at $\dot{m} \lesssim 1$ and the ion torus at $\dot{m} \lesssim 50\ (v_{inflow}/v_{freefall})^2$ (for Coulomb coupling between ions and electrons: Rees et al. 1982). A radiation torus occurs at $\dot{m} \gtrsim$ a few.

To establish the physical parameters of the environment we will be discussing below, it is worth listing some characteristic scales associated with the accretion theory;

luminosity ~ $10^{45}\ M_8 \dot{m}$ ergs s^{-1}

radius ~ $3 \times 10^{14}\ M_8$ cm

density ~ $10^9\ \dot{m}/M_8\ \mathrm{cm}^{-3}$

energy density ~ $3 \times 10^5\ \dot{m}/M_8$ ergs cm^{-3}

equipartition magnetic field ~ $3 \times 10^3(\dot{m}/M_8)^{1/2}$ Gauss.

The actual flow is likely to be much more complicated than the simple models described above. Elements of all three modes may coexist, e.g., a two-temperature corona may overlie an optically thick disk or optically thick clouds may be embedded in a hot intercloud medium. The role of magnetic fields in transporting energy from one region of the flow to another is unknown; the flow may resemble an extreme version of the solar atmosphere with magnetic flares transferring a large fraction of the available energy into low-density regions. The apparently nonthermal nature of much of the continuum luminosity may be telling us that something like this is occurring. Without going into model-dependent details, we can identify three thermal states of gas which would be preferred simply on grounds of thermal stability. These are: 1) a cool, optically thick phase at $T \sim 10^5$ K, corresponding to LTE with the energy density given above; 2) a hot, optically thin phase with an ion temperature close to the virial temperature and $T_i \gg T_e$; and 3) a phase in Compton equilibrium with the continuum spectrum at $T \sim 10^8$ K. The cool phase could account for the UV bump whether or not it takes the form of a thin accretion disk. The UV flux need not be generated internally by viscous dissipation; instead it could consist of reprocessed X-rays (Guilbert and Rees 1988; Ferland and Rees 1988). The hot phases could host nonthermal processes responsible for portions of the observed continuum, as I discuss below.

3. CLUES FROM THE CONTINUUM SPECTRUM

Figure 2 shows my theorists' cartoon version of a typical AGN continuum spectrum. Five features draw my attention:

- A turnover in the far-IR, typically at frequencies ~ 5×10^{12} Hz. Is this due to dust, synchrotron self-absorption, or a combination of both?
- A spectral index $\alpha \equiv -d\log F_\nu/d\log\nu \sim 1$ between the far-IR and the optical. In many sources the spectrum is lumpy, suggesting that a superposition of thermal components (dust?) contributes significantly to this portion of the continuum. However, some observers have suggested that a nonthermal power-law underlies the continuum, and dominates its shape in many sources (Ward _et al._ 1987; Carleton _et al._ 1987).
- The "UV bump," to which I have already alluded. Attempts to fit this feature with accretion disk spectra are discussed in these proceedings by Netzer, Laor, Sun and others. The bump often appears to cut off in the far UV, but this may be due to absorption by intervening material. If the bump extends into the soft X-rays, it could contribute to the soft X-ray excesses observed in some AGNs.

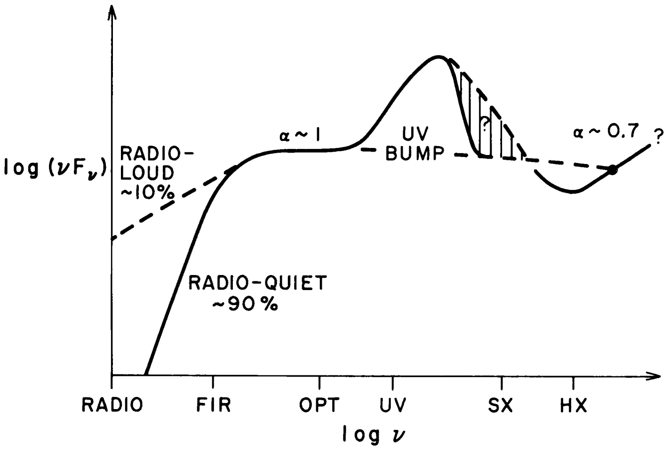

Fig. 2. Generic AGN continuum spectrum. High frequency behavior of UV bump is uncertain because of absorption by intervening material.

- A strong correlation between the IR flux and the X-ray flux at energies of a few keV. This appears to correspond to a mean spectral index slightly steeper than one, possibly with some luminosity dependence (Kriss 1988). Is this correlation a symptom of a continuous nonthermal spectrum, or is it indicative of reprocessing?
- A flattening of the spectrum into the hard X-ray band, with typical X-ray spectral indices ~ 0.7. If this slope continues up to energies approaching 1 MeV, then the hard X-ray/soft γ-ray flux dominates the radiation output of AGNs.

3.1 The IR continuum: thermal or nonthermal?

The relative contribution of thermal (dust) and nonthermal radiation to the far-IR continuum has been one of the controversial issues of this meeting. Before discussing the nonthermal scenario in detail, I will summarize some of the main theoretical points relevant to this controversy.

Synchrotron self-absorption should cause the spectrum to turn over longwards of $\nu_t \sim 10^{13}$ Hz, if the synchrotron source is located close to the black hole. Turning the calculation around, the radius of the "far-IR photosphere" is

$$R_t \sim 3 \times 10^{15} B_3^{1/4} L_{45}^{1/2} \left(\frac{\nu_t}{5 \times 10^{12}\ \text{Hz}}\right)^{-7/4} \text{cm} \quad , \qquad (1)$$

where $B_3 \equiv B/10^3$G and $L_{45} \equiv L/10^{45}$ ergs s^{-1}. Thus, the IR source must be compact if the turnover is caused by synchrotron self-absorption. Observations suggest that the far-IR flux does not vary as rapidly as one might expect if the source were this compact. Although lack of variability does not imply that a source is extended, it does suggest that the IR flux is stabilized by some kind of feedback mechanism if it is nonthermal. So far, little work has been done on the possible nature of such a feedback mechanism.

A self-absorbed synchrotron source with a power-law distribution of electrons produces a spectrum $F_\nu \propto \nu^{2.5}$ at low frequencies. $\alpha = -2/5$ is the steepest spectrum attainable; distributions resembling a Maxwellian give $\alpha \sim -2$ (de Kool, Begelman, and Sikora 1988). Detection of a steeper turnover is often taken as evidence against synchrotron self-absorption and for thermal emission by dust, since the latter can produce a much steeper spectrum. However, caution should be used in interpreting upper limits or mean slopes derived from measurements at two frequencies, since free-free absorption by an intervening screen can exponentially depress the flux at the lower frequency. Note that a screen is required to produce this effect; internal free-free absorption in the source has little effect on an intrinsic spectrum steeper than ν^2.

If thermal radiation by dust dominates the entire IR continuum, then the spectrum probably arises from the superposition of sources at different distances from the nucleus. Why, then, does the spectrum simulate an $\alpha \sim 1$ power law, albeit lumpy? Is the dust located in the disk, in the emission line clouds, or somewhere else? Does the IR flux consist of reprocessed UV or X-ray radiation from the nucleus, or is it mechanical energy which is deposited far from the black hole, perhaps by a jet or wind?

3.2 Constraints on a one-zone nonthermal model

Since we cannot yet answer any of the above questions, I will take the liberty of analyzing a simple, "one-zone" nonthermal model. The basic assumptions are that the far-IR turnover is due to synchrotron self-absorption and that at least the IR-optical continuum (and possibly the IR-X continuum) consists of synchrotron radiation with $\alpha \sim 1$. One point of this exercise is to demonstrate that existing observations impose serious constraints on models of this type. Nevertheless, it appears that a self-consistent model can be constructed.

To produce the observed spectral slope, the relativistic electrons must be distributed in energy according to $N_\gamma \propto \gamma^{-3}$, implying that relativistic electrons are injected continuously at

$$\gamma \gtrsim \gamma_t \sim 60\ B_3^{-1/2} \left(\frac{\nu_t}{5 \times 10^{12}\ \mathrm{Hz}}\right)^{1/2} \tag{2}$$

with a number injection spectrum $\propto \gamma^{-2}$. Here γ_t is the minimum Lorentz factor of a synchrotron-emitting electron which radiates most of its energy above the turnover frequency. For monoenergetic injection the spectral index would be 0.5. Under the assumed conditions, electrons with $\gamma < \gamma_t$ must lose energy at a rate comparable to the IR luminosity, but are unable to do so through synchrotron radiation. De Kool, Begelman, and Sikora (1988) and Ghisellini, Guilbert, and

Svensson (1988) have recently demonstrated in detail how synchrotron self-absorption causes the electron distribution to build a thermal peak until some other mechanism is able to drain away the accumulating energy. Where does this energy go?

Several possible sinks for the energy can be eliminated on observational or theoretical grounds. The most obvious loss mechanism is Compton scattering. However, synchrotron self-Compton scattering of the IR continuum will generally lead to a spectrum which is too flat, $\alpha < 1$ (Ghisellini 1987). If the electrons cool by Comptonizing the UV bump, then we would expect $L_{2keV} \gtrsim L_{IR}$, which is not observed (Kriss 1988). We cannot rule out the possibility that the electrons cool by Comptonizing hard X-rays. To avoid flattening the IR continuum spectrum by Comptonization, the X-ray luminosity would have to exceed both L_{IR} and the energy flux injected in electrons with $\gamma \lesssim \gamma_t$. The excess energy could also be lost through Coulomb interactions with thermal plasma. For this mechanism to be effective, the density in thermal electrons must be $\gtrsim 10^{10}$ cm^{-3}. To avoid unacceptable spectral distortions due to thermal Comptonization, the emitting region would have to be a thin shell or a corona on the surface of a disk (de Kool and Begelman, in preparation). It is unlikely that the physical removal of electrons by accretion or in a wind can seriously affect their energetics. The characteristic cooling time scale of an electron with $\gamma \sim 10$ is $\lesssim 100$ seconds, which is far shorter than the light travel time across the emission region. If the radiating particles are electron-positron pairs, then annihilation will occur too slowly to affect the energetics unless the electron scattering optical depth is unacceptably high.

We can use existing observations to place limits on the amount of thermal plasma that may be mixed with the relativistic electrons. The most stringent constraint seems to be that imposed by induced Compton scattering, which distorts the far-IR spectrum if the electron scattering optical depth in thermal plasma satisfies

$$\tau_{es} > \frac{m_e c^2}{kT_b} \sim 0.05\ B_3^{1/2} \left(\frac{\nu_t}{5 \times 10^{12}\ \mathrm{Hz}}\right)^{-1/2} \qquad (3)$$

(Sunyaev 1971; Blandford and Rees, private communication), where $T_b \sim \gamma_t m_e c^2/3k$ is the brightness temperature at the far-IR turnover. The effect of induced Compton scattering is to "chop the top" off the self-absorbed synchrotron spectrum, increasing the turnover frequency and making the turnover more gentle. This does not seem to be consistent with recent observations suggesting that the turnover is sudden and steep. Of course, a contribution by dust could mask the effects of induced Compton scattering. Two less stringent constraints on the thermal plasma are: 1) the Compton y-parameter must satisfy

$$y \equiv \max[\tau_{es}, \tau_{es}^2]\ \frac{4kT}{m_e c^2} < 1 \qquad (4)$$

to avoid flattening the $\alpha \sim 1$ power law; and 2) free-free absorption must not cut off the spectrum at a frequency above the observed turnover. Guilbert and Rees (1988) and Ferland and Rees (1988) have studied additional constraints associated with X-ray photoelectric absorption in $\sim 10^5$ K thermal gas.

It is instructive to compare these observationally inspired constraints with the amount of thermal plasma which is likely to be present on theoretical grounds. At the very least, the thermal background will consist of those cooled relativistic electrons which have not been reaccelerated or removed by some other means. The optical depth in thermal electrons satisfies

$$\tau_{es} > \left(\frac{\sigma_T L_{IR}}{m_e c^3 R}\right)\left(\frac{t_{removal}}{R/c}\right)\left[\frac{1}{\pi\gamma_{min}\ln(\gamma_{max}/\gamma_{min})}\right]_{inj} \quad , \qquad (5)$$

where σ_T is the Thomson cross section and γ_{max}, γ_{min} are the maximum and minimum injected electron energies, respectively. the first factor in brackets is similar to the "compactness parameter" familiar from studies of pair production, and has a value $\sim 30\ L_{45}(R/10^{15}\mathrm{cm})^{-1}$. The second factor compares the removal time of the thermal electrons with the light travel time across the emission region, while the third factor reflects the fact that the total number of injected electrons can be reduced if the injection process cuts off below some minimum γ. Note that γ_{min} must be at least as large as γ_t. To avoid spectral distortions by induced Compton scattering, either most electrons must be reaccelerated before being physically removed from the system, or few electrons are injected with $\gamma \ll \gamma_t$.

4. PRODUCTION OF RELATIVISTIC ELECTRONS

There are a variety of processes by which electrons in the thermal pool might be accelerated to relativistic energies, including first- and second-order Fermi acceleration and electrodynamic acceleration at sites of magnetic reconnection. In addition, the high radiation and particle densities in the central engines of AGNs provide an environment particularly conducive to the _creation_ of relativistic electrons and positrons by quantum processes. Since we do not understand particle acceleration mechanisms well enough to make quantitative predictions, I will concentrate on the quantum processes, which include inelastic proton-proton collisions, pion production by photon-proton collisions, pair production by photons in the electric field of a proton, and photon-photon pair production. The first two mechanisms are mediated by strong interactions and produce pions which eventually create pairs, while the latter two are electrodynamic processes. These mechanisms generally require the injection of _some_ relativistic particles, which I will take for granted.

The most thoroughly studied particle creation mechanism in this context is photon-photon pair production. The optical depth to pair production for a photon of energy hν > 1 MeV is given by

$$\tau_{\gamma\gamma}(\nu) \sim \frac{1}{4\pi}\left(\frac{\sigma_T L_{1\mathrm{MeV}}}{m_e c^3 R}\right)\left(\frac{h\nu}{m_e c^2}\right)^{\bar{\alpha}} \quad . \qquad (6)$$

The first factor in brackets is the compactness, defined in terms of the luminosity at energies ~ 1 MeV, and $\bar{\alpha}$ is the mean spectral index between $(m_e c^2)^2/h\nu$ and 1 MeV. Equation (6) shows that it is generally easier for more energetic photons to produce pairs, because a larger number of soft photons are available as targets. Since relativistic electrons and positrons can produce γ-rays in the process of cooling, there exists the possibility of a "pair cascade." The cycle depicted in Fig. 3 illustrates the central idea of a pair cascade. Some of the kinetic energy associated with relativistic pairs is transformed into γ-rays through a cooling process (e.g., inverse Compton scattering). The γ-rays are then absorbed in pair-producing interactions with soft photons, completing the cycle. Each successive cycle produces a generation of pairs, which adds to the total electron injection function. This process can steepen the resulting energy distribution and the observed spectrum if the number of pairs at a given energy exceeds the number of primary (injected) electrons. The effect of a pair cascade on the electron energy distribution is shown schematically in Fig. 4, for the case where primary electrons are injected in a spike at some fixed energy. The dashed lines illustrate the energy distributions associated with successive generations of pairs. In the limit of a large number of generations and small losses (a "saturated" cascade), the energy distribution tends to γ^{-3} and the spectral index tends to $\alpha \sim 1$. A pair cascade has little effect on the spectrum if the primary electron distribution is steeper than γ^{-3}.

The properties of a pair cascade depend on a number of parameters, including the maximum Lorentz factor of injected electrons (γ_{max}), the energy injection rate (L_{inj}), the typical energy of soft photons ($h\nu_{soft}$), the soft photon luminosity (L_{soft}), and the ratio of magnetic energy density to radiation energy density (U_B/U_{rad}). Systems in which $\gamma_{max}(h\nu_{soft}/m_e c^2) \lesssim 1$ may produce 1 - ~3 generations of pairs and spectral indices in the range ~ 0.6 - 0.8 (Zdziarski and

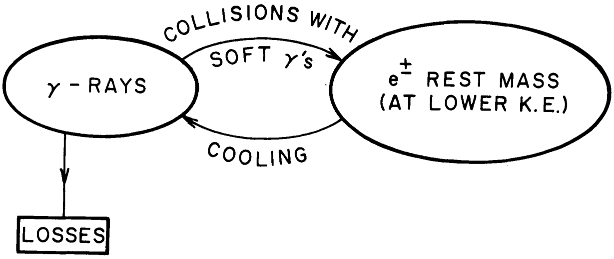

Fig. 3. Basic cycle responsible for pair cascades.

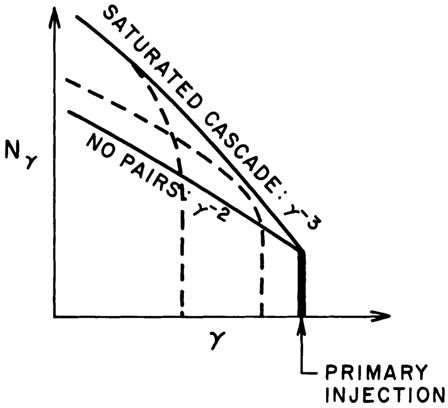

Fig. 4. Effect of a saturated pair cascade on the electron energy distribution.

Lightman 1985; Fabian et al. 1986; Svensson 1987). The authors just cited have suggested that such partially saturated cascades could explain the observed uniformity of hard X-ray spectral indices in many AGNs. Highly saturated cascades with $\alpha \sim 1$ probably require $\gamma_{max}(h\nu_{soft}/m_ec^2) \gtrsim 1$, $U_B/U_{rad} \gtrsim 1$, and a sufficiently large γ_{max} (Ghisellini 1987; de Kool and Begelman, in preparation).

Without understanding the primary particle acceleration mechanisms in detail, we can place upper bounds on γ_{max} by equating the acceleration time with the radiative cooling time. For direct hydromagnetic acceleration of electrons, e.g., by Fermi acceleration, sychrotron losses limit γ_{max} to $\lesssim 10^6\ B_3^{-1/2}$ (Phinney 1983; Rees 1984). However, considerably higher values of γ_{max} are possible if primary relativistic pairs are injected by quantum processes involving relativistic protons, instead of being accelerated (Sikora et al. 1987). If the protons are accelerated by hydromagnetic processes, γ_{max} for the primary pairs may be as large as $10^{10}\ \ell^{-1/4}(U_B/U_{rad})^{1/4}$, where ℓ is the compactness. An inevitable consequence of proton acceleration is the production of a flux of relativistic neutrons which escapes the central engine. The consequences of the neutron flux are described elsewhere in this volume by Sikora, Rudak and Begelman.

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DISCUSSION

BIERMANN Just a reminder: VLBI has observed active nuclei at scales of 10^{14} cm (our Galaxy), 10^{16} cm (M 81), and $10^{-4''}$ at 7 mm wavelength (recent Nature paper), thus demonstrating structure – the only direct evidence – in that region which many believe to encompass the broad line region.

BEGELMAN Unfortunately, the observations on extremely small scales ($\ll 10^{17}$ cm) must be confined to low luminosity AGNs. The high luminosity ones are self-absorbed on small scales. It is true that VLBI observations are possible in many sources on scales > 0.1 - 1 pc. This is believed to be the scale of the broad line region in fairly luminous AGNs.

GASKELL How do you propose to accelerate a pair plasma in a jet?

BEGELMAN A pair-dominated plasma has a lower Eddington limit than an electron-ion plasma, so radiative acceleration is one possibility. Hydromagnetic acceleration mechanisms – variants of the old solar wind model of Weber and Davis – are very attractive because they seem to account for the initial collimation in a natural way, through magnetic stresses. Pairs are attractive in this context as well, because they can be accelerated to high speeds (if the radiation drag is not too strong). Pairs can be created in the wind acceleration zone by photon-photon collisions, thus providing a simple way to inject the mass flux at the base of the wind.

G. BURBIDGE There is only a consensus concerning black holes and accretion because the alternative "so-called New Physics" is considered unpalatable. However, one way of deciding whether or not the conventional view is correct is to make an honest estimate of the efficiency of the process. If it is as small as 10^{-3} or 10^{-4} as I suspect, then the matter required for the conventional view to be correct will be far too high. What is your honest estimate of the efficiency of conversion of gravitational energy into the energy we see – photons, electrons, radio lobes, everything? Also if relativistic protons are a fundamental source they will lead to spallation of C, N, and O in the gas clouds, leading to the build-up of Li, Be, or B. About ten years ago some of us discussed this and attempted to set limits on these abundances by detecting a line due to boron, if I remember correctly.

BEGELMAN An efficiency of a few percent is not unreasonable. After all, the standard thin accretion disk theory predicts an efficiency which is at least this high (and can be higher for an extreme Kerr hole). Likewise, the Blandford-Znajek mechanism can be rather efficient at extracting energy from a rotating hole. I agree with you that black holes would lose much of their appeal if the efficiencies were as low as 10^{-3} or 10^{-4}. As for your point about spallation, I don't think it will lead to observable effects for the conditions I am discussing. In my picture, the only cosmic rays which reach pc scales are the neutrons which survive the trip. These have enormous energies, and there are not very many of them. My quess is that the number of spalled nuclei would be too small to be observable.