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GAMMA RAYS FROM PENROSE POWERED BLACK HOLES IN CENTAURUS A, 3C 273, AND NGC 4151

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ABSTRACT

Gamma-ray observations of active galaxies have important consequences for theories of the activity in their nuclei. The observations of Cen A, 3C 273, and NGC 4151 are examined under the assumption that Penrose collision processes in the ergospheres of massive black holes power their nuclei. The observed sharp break in the MeV region of the NGC 4151 spectrum cannot be due to the γ-γ pair production process. We attribute this break to the Penrose Compton scattering (PCS), in which γ-rays escape from the ergosphere as a result of Penrose processes involving electrons and lower energy X-ray photons in the ergosphere of the black hole. The absence of an MeV break in the spectra of Cen A and 3C 273 argues in favor of the Penrose pair production (PPP), in which high-energy pairs (a few GeV in energy) escape as result of Penrose processes involving protons and γ-rays that are present in any hot, optically thin, vertically extended accretion disk. An intrinsic break in the GeV region is predicted for both Cen A and 3C 273 as well as any other PPP powered nucleus. The mass of the black hole, the accretion rate, the efficiency of accretion, etc., are obtained self-consistently under the assumption that γ-γ scattering is unimportant below $\sim$10–100 MeV. This assumption is very reasonably based on the observations. Central black hole masses of tens of millions solar masses for NGC 4151 and Cen A, and tens of billions solar masses for 3C 273, are obtained. Even though fewer Penrose produced pairs are emitted along the rotation axis of the hole, they suffer smaller energy losses in that direction, and therefore PPP has built into it the possibility of contributing to the explanation of the lobes of radio galaxies. The effect of "aging" of the active nucleus may account for some of the differences among different types of Seyferts (and presumably QSOs) since objects which are spinning close to the canonical value of $a/M = 0.998$ would have Penrose processes but not those which have slowed down their spin. If PPP is important for QSOs and radio galaxies and some Seyferts, we expect powerful radio objects to be also powerful γ-ray objects. Nuclei in which the black hole is spinning slowly would still emit visible light, UV, and X-rays as result of accretion without Penrose processes but would be weak in radio or high-energy γ-rays. Future γ-ray observations should provide clues as to whether this scenario is correct. Besides spectral information at γ-ray frequencies, possible variability at γ-ray frequencies should be searched for.

Subject headings: black holes — galaxies: nuclei — galaxies: Seyfert — gamma rays: general — quasars

I. INTRODUCTION

Recent γ-ray observations of some active galaxies should provide important information for theories of the origin of activity from such objects. The surprising result that a large portion of the luminous output of active galaxies like 3C 273 and NGC 4151 is in the γ-ray region of the spectrum has important consequences for the understanding of the activity associated with active galaxies and quasars.

One theory, recently proposed by Leiter and Kafatos (1978) and Kafatos and Leiter (1979) (Papers I and II, respectively), attributes the energy generation within the active nucleus to Penrose processes; these processes take place in the ergosphere of a massive Kerr black hole that presumably exists in the center of the activity. High-energy photons, falling in toward the horizon, are blueshifted in energy in the "local nonrotating frame" (LNRF) (Bardeen, Press, and Teukolsky 1972) by factors between 10 and 30. Two processes that will readily take place as long as an ample supply of γ-rays enters the ergosphere are the following: (1) "Penrose pair production" (PPP) in which a blueshifted γ-ray (with energy in the approximate range a few tens of MeV to a few GeV) scatters off an infalling proton, injecting it and producing pairs that subsequently escape with energies that may be as high as $\sim 4m_pc^2$, (2) "Penrose Compton scattering" (PCS) in which a blueshifted γ-ray (with energy less than a few MeV) scatters off an infalling electron, injecting it and then escaping with an energy that may be as high as $\sim 4m_ec^2$.

There are other Penrose processes that can take place—e.g., the disintegration process $\pi^0 \rightarrow 2\gamma$. For this process, the maximum energy of the escaping photons is not larger than what one would expect for flat spacetime (Piran and Shaham 1977*b*). These other processes are relatively inefficient and will not be considered here.

The Penrose pairs that are produced in the PPP process are relativistic and could explain the synchrotron emission and inverse Compton emission that are associated with active galaxies. In the theory discussed in Paper II one would expect both thermal and nonthermal radiation associated with the active nucleus, whereas other black hole theories predict thermal radiation; where "Comptonization" is utilized (cf. Katz 1976), the electron distribution is still thermal. Moreover, these Penrose processes can take place only during periods of instability when the inner ergosphere is filled up with plasma; therefore, variability is associated in a fundamental way with this theory.

In Paper I, PPP was examined for "extreme" Kerr metrics (with $a/M \approx 1$, where a/M is the angular momentum density in natural units, $c = G = 1$). It was found that the extreme values of a/M associated with this process would, most likely, have to be associated with primordial turbulence. In Paper II, PPP was examined in the astrophysically plausible scenario of "canonical" Kerr black holes, having $a/M \approx 0.998$ that has been shown by Thorne (1974) to be the asymptotic limit of the angular momentum density of a Kerr black hole. Conditions were derived in Paper II for PPP to be operating, and it was found that self-consistent results could be obtained as long as γ-rays were emitted by a spatially thick, hot inner region of an accretion disk.

Hot, inner regions, from which γ-rays can be emitted, are predicted by the two-temperature model (Shapiro, Lightman, and Eardley 1976), the optically thin model (Pringle, Rees, and Pacholczyk 1973; Payne and Eardley 1977), and the hot corona model (Liang and Price 1977; Bisnovatyi-Kogan and Blinnikov 1976) in which a hot corona exists around a "standard" disk (Shakura and Sunyaev 1973; Novikov and Thorne 1973).

The predictions of the Penrose theory examined in Paper II and in the present paper depend on the spin of the black hole. This was assumed to have the canonical $a/M \approx 0.998$ value suggested by Thorne (1974). Although Thorne showed that the detailed evolution of the spin of the black hole depends on the specific scenario assumed, he also showed that the canonical value would be the asymptotic limit under different conditions. In § V we briefly examine what would happen if the spin of the black hole slowed down below this value. In connection with this, the possibility that the active nucleus "ages" is suggested.

The PPP theory presented in Paper II was for radial photon infalls and tangential matter orbits (see also Piran and Shaham 1977*b*). The latter are certainly reasonable, particularly for periods of rearrangement of the flow pattern. Radial photon infalls give a good estimate of the average process: photons which go against the spin of the black hole give higher blueshift; those going with the spin, lower blueshift, than in the radial case. Averaging over angles will eventually have to be performed, although the general results are not expected to be too different.

In Paper II, the optical depths necessary for PPP to take place were computed, and it was found that a hot, bloated inner disk is required. A narrow range of optical depths is not required; rather, the optical depths for pair production outside the ergosphere should not be too high, otherwise too few γ-rays would reach the target region. This requirement is not too stringent, and it was found that for all three active galaxies this optical depth is smaller than ~ 0.1 (§ V). On the other hand, the PPP optical depths are larger the more powerful the active nucleus (in this case 3C 273). PPP optical depths were not greatly exceeding 1 even for 3C 273, indicating that the production of relativistic electrons does not require special conditions, i.e., high optical depths in the target region. The increase of the pair-production optical depth as the target region is approached is naturally occurring due to the increase of the proper length and the density of matter and does not require any special assumptions.

In § IV approximate values of the black hole parameters are computed. Those were obtained by attributing the γ-rays from NGC 4151 to the PCS process; the fact that the observed 2 MeV break cannot be due to the γ-γ scattering process places a lower limit on the mass of the black hole. In the case of Cen A and 3C 273 the γ-ray spectra are attributed to the PPP mechanism. Besides taking into account the absence of γ-γ scattering, at least for γ-rays $\sim$10–30 MeV, the 1–100 MeV γ-rays were fitted to π^0 spectra. In this way, the mass of the black hole, the accretion rate, the efficiency of turning accreted mass into radiated energy, and the viscosity parameter were estimated. The theoretical values of the viscosity parameter α are, of course, hard to compute. The semiempirical values obtained in this paper can only be rough estimates. The justification for using steady-state accretion disks to estimate these parameters lies in the fact that, during periods of rearrangement of the flow pattern, steady-state accretion computations are expected to be approximately valid (Paper II); they, therefore, can be used as an input. Also, the fitting of the γ-ray spectrum to a hot (π^0 emitting) disk is justified because without such a disk PPP would not take place. It is hoped that in the future time-dependent calculations of hot, spatially thick disks will be carried out. Until that time, one cannot hope to pin down the values of the parameters more than was done in this paper. Even without that, though, the present work illustrates that X-ray and particularly γ-ray observations are of great value not just in checking the Penrose theory but in ultimately checking out quantitatively whether massive black holes power active galaxies.

In view of the implications of the γ-ray observations of active galaxies it is important to examine the Penrose processes and see whether these observations can be explained. It is noted here that because the Penrose pairs have their origin in the γ-rays emitted by the hot inner region around a black hole, γ-ray observations and their interpretation are important not just in themselves but in ultimately understanding the entire active galaxy phenomenon.

II. OBSERVATIONS

X-rays have been observed from a variety of active galaxies (Gursky and Schwartz 1977). Moreover, at least three active galaxies emit energy in γ-rays: (*a*) NGC 5128 or Cen A, a nearby giant radio galaxy, (*b*) NGC 4151, a nearby Seyfert galaxy, and (*c*) 3C 273, a quasar.

In this paper we concentrate on these three objects in view of their γ-ray emission and the implications for Penrose processes. The observations in the X-ray and γ-ray region of the spectrum can be summarized as follows.

a) *Centaurus A*

This radio galaxy has been observed in the 2–20 keV region by Stark, Davison, and Culhane (1976). At higher energies, in the 30 keV–12 MeV region, it has been observed by Hall *et al.* (1976). They found a good fit to the continuum radiation of the form $0.86 \times E^{-1.9}$ photons cm^{-2} s^{-1} keV^{-1}, where E, the photon energy, is given in keV. Grindlay *et al.* (1975) detected γ-rays from Cen A at energies greater than 300 GeV. Cen A is variable at X-rays, with a power-law output that varies by more than a factor of 6 (Gursky and Schwartz 1977). This variability may be as high as a factor of 25 at 100 keV over a period of 2 years (Beall *et al.* 1978), while Delvaille, Epstein, and Schnopper (1978) report a 25% increase in intensity from the point source in the nucleus over a period of 2–5 hours. The 1975 January observations of Stark, Davison, and Culhane (1976) fit the power law spectrum of Hall *et al.* (1976) at higher energies. It is interesting to note (Culhane 1978) that the shape of the spectrum remained the same throughout the X-ray observations, even though the total power varied.

In Figure 1 the power law spectrum of Cen A observed by Hall *et al.* (1976) is shown as a solid line; the dashed line extension with the break at 2 GeV will be discussed in § III. The observation of Grindlay *et al.* (1975) is shown at 300 GeV as well as the upper limits of Bignami *et al.* (1979) in the region 40–200 MeV. Note that the upper limits of Bignami *et al.* (1979) are a factor of 6 below the power law of Hall *et al.* (1976); this could be due to variability since, at least at 100 keV, the intensity from 1972 to 1975 varied by a factor of 4–5.

b) *NGC 4151*

This Seyfert galaxy has been observed by a variety of observers. For a summary of the observations see Schönfelder (1978) and Bignami *et al.* (1979). An important feature of the observations is a break in the region 2–4 MeV (Schönfelder 1978) recently confirmed by Bignami *et al.* (1979). In Figure 1 the power-law fits to the observations are shown as solid lines. The power-law fit for energies below ~3 MeV is of the form $4.5 \times 10^{-3} E^{-1}$, while above ~3 MeV it is $4 \times 10^4 E^{-3}$ photons cm^{-2} s^{-1} keV^{-1} where E is in keV. The break of the spectrum is shown, as well as the upper limits of Bignami *et al.* (1979) which confirm the high-energy power-law fit.

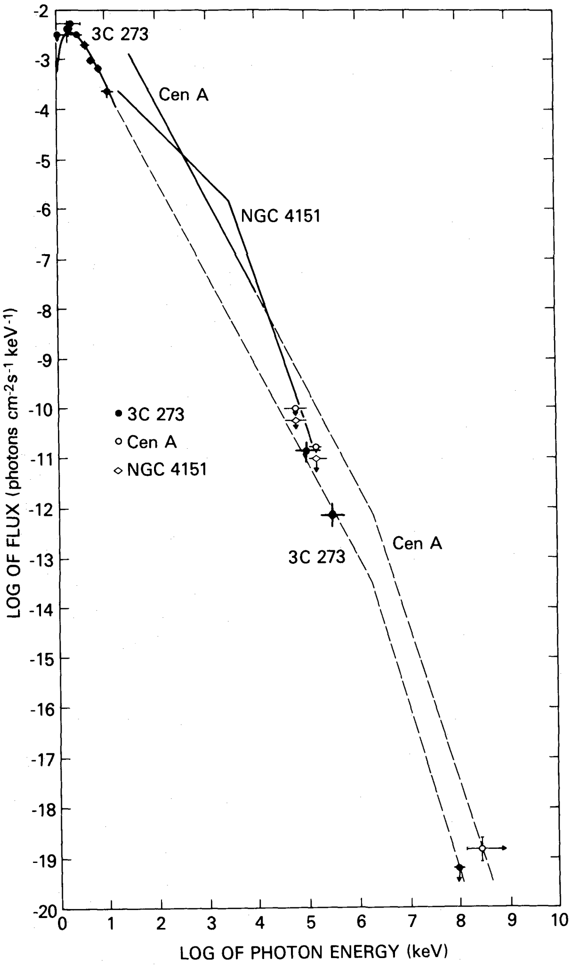

FIG. 1.—X-ray and γ-ray spectra of Cen A, NGC 4151, and 3C 273. Cen A data from Hall *et al.* (1976) in full line; upper limits from Bignami *et al.* (1979) and the 300 GeV observation of Grindlay *et al.* (1975) are shown as ○. NGC 4151 data from Schönfelder (1978) in full line; upper limits from Bignami *et al.* (1979) are shown as ◇. 3C 273 data below 10 keV, shown as ●, and power law fit to the data are from Culhane (1978); *COS B* observations reported by Swanenburg *et al.* (1978) and upper limit at 100 GeV from Helmken and Weeks (1978) are shown as ●. The mathematical form of the power law spectra is given in the text. For Cen A and 3C 273 the data have been extended to higher energies (*dashed lines*), and a PPP predicted break has been placed at 2 GeV. The 2 MeV break of the NGC 4151 spectrum is attributed to the PCS process (see text).

Recent balloon observations of NGC 4151 by Zanrosso *et al.* (1979) failed to show the existence of the MeV break. Upper limits in the 1–20 MeV spectral region were obtained. It is only, however, their 1.2–3 MeV upper limit which is less by a factor of 10 than the power-law fit quoted above. The other upper limits do not disagree with this power law. Since

NGC 4151 is a rapidly varying source of X-rays, it is not clear if the observations by Zanrosso *et al.* (1979) contradict the previous observations. There is a great need for simultaneous observations at X-ray and γ-ray energies of NGC 4151.

c) 3C 273

This quasar has been observed by numerous observers. The *Ariel 5* observations below 10 keV are shown in Figure 1 with the power-law fit to the data $2.3 \times 10^{-2} E^{-1.9}$ photons cm^{-2} s^{-1} keV^{-1}, where E is in keV, as reported by Culhane (1978). The 50–500 MeV *COS B* observations of 3C 273 reported by Swanenburg *et al.* (1978) are also shown. At 100 GeV there is an upper limit to the flux (Helmken and Weeks 1978) which is also shown.

In Figure 1 the extrapolated spectra of Cen A and 3C 273 are also shown as dashed lines. No break in the MeV region has been detected in the spectra of these two objects. Both spectra, however, must have a break at higher energies if the upper limit at 100 GeV for 3C 273 and the observation of Cen A at 300 GeV are not to be exceeded. The observations are consistent with the existence of a steep break in both spectra at ~2 GeV as expected from PPP (see § III). Moreover, the shapes of both spectra are remarkably similar, at least at X-ray energies and maybe at higher energies as well. This may not be too surprising in view of the similarities of QSOs and radio galaxies, both believed to be associated with giant elliptical galaxies. We note that a steep (say by more than unity in the exponent) break in 3C 273 does not exist below ~500 MeV, whereas a break in the Cen A spectrum much less than 2 GeV (say at some tens of MeV) would produce a power law that would miss the 300 GeV observations. It would be extremely important for these two objects, particularly for Cen A which exhibits rapid variability at X-rays, to have simultaneous observations at X-ray and γ-ray energies.

III. SPECTRA AND CUTOFFS FOR PENROSE PROCESSES

In what follows we postulate the existence of massive, Kerr black holes in the centers of the three active galaxies under consideration. In view of the recent observations of M87 (Young *et al.* 1978) this is a plausible assumption.

We concentrate here on the question of the spectral breaks and mention only a few possibilities for the detailed nature of X-ray and γ-ray spectra. Detailed spectra for the Penrose processes will be presented in a later paper.

We first examine the X-ray and γ-ray spectra in other black hole theories. For example, spherical accretion onto a Kerr black hole (Shapiro 1974) has the right energy dependence $E^{-1.3}$ below ~3 MeV that could explain the spectrum of NGC 4151; at higher energies the theoretical spectrum drops sharply (above 10 MeV). The parameters of the interstellar gas (density and temperature) at infinity required to fit the NGC 4151 observations are, however, unreasonable; the values of the parameters are obtained by scaling the results to the NGC 4151 observations and satisfying the conditions appropriate for bremsstrahlung cooling under adiabatic conditions.

The spectra calculated by Cunningham (1975) do not fit any of the three objects. The two-temperature model (Shapiro, Lightman, and Eardley 1976) was used in Paper II to provide the required γ-rays for PPP to operate. One may ask whether the spectra calculated by Shapiro, Lightman, and Eardley (1976) fit the X-ray and γ-ray spectra of the three active galaxies; in other words, one may ask what the disk contribution to the emitted energy is, without taking into account any Penrose processes. The published spectra, which hold for a nonrotating black hole, would be appropriate below a few hundred keV. The two-temperature model gives a spectrum (photons cm^{-2} s^{-1} keV^{-1}) proportional to E^{-2} for $E < kT_e$, where T_e is the electron temperature, and a steepening ("knee") to an $E^{-4.5}$ law for higher energies. Studying the NGC 4151 spectrum (Schönfelder 1978) below ~100 keV shows that it is steeper than the E^{-1} law evident in the range 100 keV–2 MeV, and consistent with an E^{-2} law. The two-temperature model is, therefore, consistent with the exponent of the power-law spectra of all three objects below ~100 keV. Moreover, when one uses the appropriate values of the inner region and the accretion rate (see Table 1) to compute the X-ray luminosity from the inner region of the disk in the two-temperature model (see Shapiro, Lightman, and Eardley 1976), one finds that the values computed agree to within a factor of 2 with the observed values below 100 keV.

The unexpectedly high γ-ray luminosities of Cen A, 3C 273, and NGC 4151 and the specific spectra have not been examined theoretically up to now. In fact, a number of workers in the field have predicted essentially no emission above 1 MeV for objects like NGC 4151 (see Lightman, Giacconi, and Tananbaum 1978).

High γ-ray luminosities are expected in a natural way in Penrose models of active galaxies (Papers I and II): When PCS operates, MeV γ-rays are expected which are the result of the scattering of lower-energy X-rays by electrons deep inside the ergosphere. When PPP operates, γ-rays would be emitted from the hot, inner region of the accretion disk (e.g., in a two-temperature model with a Kerr black hole) and by the relativistic electron-positron pairs which are the product of the Penrose scattering of the infalling γ-rays with the protons deep inside the ergosphere. Whenever a hot, extended, and optically thin region exists near the ergosphere (as in the two-temperature model, the hot corona model etc.), PPP will readily take place, given reasonable conditions (Paper II). PCS would occur in other accretion disk scenarios as well, since lower-energy X-rays are required for this process.

As we saw in § I, there is a maximum energy of the ejected photons in the PCS process and of the ejected pairs in the PPP process. In fact, any Penrose quantum process would have a cutoff in the energy of the ejected particles or photons (Paper II). The ejected pairs contribute a major portion of the observed high-

TABLE 1

BLACK HOLE PARAMETERS FOR CENTAURUS A, 3C 273, AND NGC 4151

$E_{\gamma\gamma}$ (MeV) (1)	M_8 (2)	r_{0*} (3)	α (4)	$\dot{M}_1$ (5)	β_1 (6)	$\mathscr{R}$ (7)	$(r_{0*}r_g)/c$ (8)
Centaurus A[a]							
10........	0.035	24	0.15	1.4×10^{-2}	0.23	2.7×10^{-2}	7 min
30........	0.35	11	0.15	4.3×10^{-2}	7.7×10^{-2}	2.7×10^{-3}	32 min
100........	0.85	8	0.17	7.5×10^{-2}	4.4×10^{-2}	1.1×10^{-3}	54.5 min
3C 273[a]							
10........	30	28	0.13	10.8	0.31	3.1×10^{-2}	4.9 d
30........	110	18	0.13	21.2	0.16	8.5×10^{-3}	11.5 d
100........	600	10	0.14	51.4	6.5×10^{-2}	1.6×10^{-3}	34 d
NGC 4151[b]							
....	0.5	$\gtrsim 15$	...	0.13	0.25	7.7×10^{-2}	$\gtrsim 1$ hr

[a] For Cen A and 3C 273, PPP holds.

[b] For NGC 4151, PCS holds.

NOTE.—All parameters, other than $E_{\gamma\gamma}$ and $(r_{0*}r_g)/c$, are dimensionless. $E_{\gamma\gamma}$ is the γ-ray energy at which $\tau_{\gamma\gamma} = 1$ (for Cen A it is at least 10 MeV); M_8 is the mass of the black hole in $10^8\ M_\odot$ and is the minimum value for the particular $E_{\gamma\gamma}$ values assumed if all lengths are equal to a common value r_{0*} (see text); r_{0*} is this size in gravitational units; α is the viscosity parameter; $\dot{M}_1$ is the accretion rate in $M_\odot\ \mathrm{yr}^{-1}$; β_1 is the efficiency of the accretion process; $\mathscr{R}$ is the ratio of the luminosity L to the Eddington value L_{Ed}; the last column gives the light travel time for the hot, inner region which emits γ-rays and could be the variability time scale for γ-rays. These parameters were computed for $f = 1$ (see text). For other values of f, multiply each quantity by the factors given in (A4) of the Appendix. For NGC 4151 the product $M_8 r_{0*}$ has a lower limit from the observations. The values given correspond to $M_8 = 0.5$ and $\beta_1 = 0.25$ (see text).

energy γ-rays through relativistic bremsstrahlung and other radiation processes. Cutoffs in the MeV region are expected when PCS is the dominant process and in the GeV region of the spectrum when PPP is the dominant process.

An MeV cutoff may be produced by "Comptonization" (Shapiro, Lightman, and Eardley 1976; Katz 1976) at $(2\text{–}3)kT_e$. Electron temperatures $T_e \sim 10^{10}$ K would be required for explanation of the NGC 4151 break. However, Comptonization could not account for the required break above 500 MeV for 3C 273. Penrose processes can account for the observed MeV break in the spectrum of NGC 4151 and the expected (presumably) GeV break in the spectra of 3C 273 and Cen A.

Detailed γ-ray spectra have been presented in the case of PCS processes by Piran and Shaham (1977*a*). The majority of the cases examined by Piran and Shaham refer to a fairly thin spatial distribution of incoming matter ($\pm 10°$ from the equatorial plane). The majority of the Penrose ejected γ-rays in these cases (or Penrose ejected pairs for PPP) are found at angles less than 40° from the equator (cf. Piran and Shaham 1977*a*). A hotter—and wider—disk that is required by the analysis of Paper II will produce harder spectra. In preliminary calculations we find that the E^{-1} power-law spectrum of NGC 4151 can be reproduced in a model with infalling matter distributed more than $\pm 40°$ from the equatorial plane and with $T_e > 10^9$ K. The break should then occur at ~ 2 MeV, consistent with observations (see also Leiter and Kafatos 1979).

When PPP operates, part of the γ-rays emitted are due to the π^0 spectrum from the hot, inner region. The rest of the γ-rays are the result of the radiation processes of the ejected high-energy pairs: inverse Compton scattering, relativistic bremsstrahlung, and synchrotron radiation. Inverse Compton would give rise to scattered photons of energy $\sim\gamma^2\ h\nu$ for incident energies less than $\sim mc^2/\gamma$ (where $\gamma \sim 2000$ for electrons of energy 1 GeV), and to scattered photons of energy $\sim\gamma mc^2$ for photon energies greater than $\sim mc^2/\gamma$; relativistic bremsstrahlung would give rise to maximum photon energies of γmc^2; if magnetic fields as high as 10^6 gauss exist near the black hole (Rees 1978), synchrotron radiation would give rise to photons of energies as high as ~ 200 keV, with some photons of energies extending to the MeV region of the spectrum.

Inverse Compton scattering, relativistic bremsstrahlung, and synchrotron radiation would be important inside the disk: the last two because matter is required if ions are to be present or magnetic fields to be present; on the other hand, inverse Compton is expected to be negligible along the axis of rotation of the black hole since at that direction one would expect very few photons; inverse Compton would be most important near the disk where the energy density of radiation is highest. It follows that the ejected pairs would suffer few losses along or near the axis of rotation, and therefore PPP has built in a direction of focusing of relativistic electrons. At angles not large above or below the equator, where the pairs impinge on the hot, extended, optically thin region, they would suffer the greatest losses, even though more of them get ejected within ±40° from the equator. Whether or not they would escape from the hot, inner region depends on the ratio of the radiation length (computed for all three energy loss mechanisms) to the characteristic dimension of the hot region. Farther out, where the disk becomes thinner, only pairs emitted close to the equator would suffer losses.

Assuming that nonthermal processes (synchrotron and inverse Compton) dominate the emission in the disk, the Cen A and 3C 273 data yield a power law of index $\alpha \sim 0.9$ for the spectral flux density S_ν, where $S_\nu \propto \nu^{-\alpha}$ and its units are keV cm^{-2} s^{-1} keV^{-1} or W m^{-2} Hz^{-1}. This corresponds to a power-law spectrum of the relativistic electrons of index $\Gamma = 2.8$, where $\alpha = (\Gamma - 1)/2$ and the electron spectrum is given by $I_e(E_e) = I_e E_e{}^{-\Gamma}$. If relativistic bremsstrahlung dominates, then the spectral flux density is $S_\nu \propto \nu^{-\Gamma}$ and therefore the observed photon flux at X-rays and γ-rays yields $\Gamma \sim 0.9$. It is interesting to note that the range of the index of the spectral flux density in the radio is $\sim$0.9 and $\sim$0 for the two limiting cases (nonthermal processes and thermal processes), and this is the approximate range of the observed radio indices for the majority of the extragalactic radio sources.

Penrose processes produce power-law spectra at high energies (see also Piran and Shaham 1977*b*). This is in contrast to thermal spectra which have an exponential behavior. The detailed spectrum observed by an observer at infinity depends, among others, on the temperature of the particles, the energy of the infalling photons, the a/M ratio of the black hole, the optical depth for the process, the density of the (target) particles, the parameter Q, etc. (see also Piran and Shaham 1977*b*). It also depends on the angle of observation; for large angles relative to the equator, the spectrum is softer than for small angles. Generally, power-law spectra of the ejected photons for PCS (and the ejected electron-positron pairs for PPP) with indices between $\sim$1 and $\sim$3 result. High input particle temperatures and small observer angles produce harder spectra. Moreover, for $Q \neq 0$ (i.e., spatially thick disks) and for higher optical depths, the fraction of pairs escaping close to the axis of rotation increases (see Piran and Shaham 1977*a*, *b*). We should point out, though, that the numerical results of Piran and Shaham (1977*a*) indicate that the fraction of PCS produced γ-rays emitted between 45° and 90° from the equator varies between approximately 5% and 30% in all cases they tabulated. Even though the results of Piran and Shaham apply to the PCS process, we expect that these results should be qualitatively similar for PPP. It follows that the fraction of ejected pairs close to the axis of rotation is not negligible. From the previous discussion of the spectral indices it follows that the observed spectra are consistent with Penrose processes.

We now turn to the question of the Penrose cutoffs which are an important signature of the theory.

In any Penrose scattering process a cutoff arises because the farther in near the horizon the process takes place, the higher the energy extracted; on the other hand, the harder it is for the scattered particle to escape. An upper limit to the energy of the ejected particles results. The exact location of the upper energy cutoff depends on the specific accretion scenario (like the spectrum). However, this energy is specified primarily by the rest mass of the injected particle and therefore would be found in the MeV region for PCS and in the GeV region for PPP. In general it is in the range $(2\text{–}4)mc^2$, where m is the rest mass of the Penrose injected particle, unless one is viewing the disk along the rotational axis, in which case it is less. The higher energy cutoffs are found for the hardest spectra.

The NGC 4151 cutoff is expected to be found at $\sim$2 MeV, consistent with the hard (E^{-1}) spectrum. For PPP the break should occur in the 1–4 GeV region of the spectrum, with a possible location at $\sim$2 GeV; this happens because it is more likely that each member of the pair will share equally in the available energy. We point out that even above $\sim$2 GeV, PPP operates appreciably due to the presence of helium nuclei. The pair-production cross section is proportional to Z^2, where Z is the charge of the nucleus. It follows that the mean free path for pair production off helium is 10/4 that due to hydrogen. A helium cutoff would be located in the 4–16 GeV region of the spectrum. At high energies the spectrum should be dropping steeply.

The probable location of the PPP cutoff is shown in Figure 1 for the spectra of Cen A and 3C 273. This prediction of the Penrose theory should be tested in the future with γ-ray satellites. It is unlikely that any other theory will predict a break of the γ-ray spectra of quasars and radio galaxies in the GeV region of the spectrum.

IV. BLACK HOLE PARAMETERS FOR NGC 4151, CENTAURUS A, AND 3C 273

Gamma-ray observations have important implications for the size of the γ-ray source. This is due to the fact that a compact, luminous source of γ-rays is subjected to the well known γ-γ scattering process, whereby pairs are produced (cf. Jelley 1966*a*, *b*; Pollack, Guthrie, and Shen 1971; Herterich 1974). The process is unavoidable in compact, strong γ-ray sources (Cavallo and Rees 1978). McBreen (1978) considers γ-γ scattering in 3C 273 and concludes that the γ-ray source size should be more than 1 pc.

We examine here the implications of the γ-γ scattering process for the γ-ray observations of Cen A, 3C 273, and NGC 4151. We, of course, assume that a massive black hole resides in the centers of these galaxies.

The optical depth for γ-γ can be written as (cf. Herterich 1974)

$$\tau_{\gamma\gamma} = r_1 \int_{E_T}^{\infty} n(E)\sigma dE\,, \qquad (1)$$

where the threshold energy of the photons E_T is given by

$$E_T = 2mc^2/[(1 - \cos\theta)E]\,. \qquad (2)$$

In (2), θ is the angle between the momentum vectors of the two photons. It is sufficient in this paper to assume $\cos\theta = \frac{1}{2}$.

In (1), $n(E)$ is the density of photons, which scatter the γ-rays, per unit energy; r_1 is the size of the source; and σ the cross section for γ-γ scattering. This cross section rises steeply from a threshold E_T, has a maximum value at $E = 2E_T$, and falls off as E^{-2} for photon energies $E \gg E_T$. Following Herterich (1974), we approximate σ by a rectangular function with height $\sigma_0 = 1.7 \times 10^{-25}$ cm^2 and width $2.5E_T$. We substitute for n in (1) the formula

$$n(E) = [F(E)4\pi D^2]/(4\pi r^2 c)\,, \qquad (3)$$

where D is the distance to the source and $F(E)$ is the photon flux at the Earth (in photons cm^{-2} s^{-1} keV^{-1}). We write the size of the γ-ray absorption region r_1 in terms of the gravitational radius r_g, where $r_g = 1.5 \times 10^{13}\, M_8$ cm and the mass of the black hole is $10^8\, M_8$ solar masses, as $r_1 = r_{1*} r_g$. It then follows that

$$\tau_{\gamma\gamma} \approx \frac{D^2{}_{\mathrm{Mpc}} 9 E_T(\mathrm{keV}) F(2E_T)}{r_{1*} M_8}\,, \qquad (4)$$

where we set $\tau_{\gamma\gamma} = 1$ below and where $F(2E_T)$ is the flux (photons cm^{-2} s^{-1} keV^{-1}) at an energy $E = 2E_T$ (keV). In (4), F is taken from Figure 1 for the three sources examined here.

Formula (4) may be used to obtain estimates of the mass of the black hole, M_8, if the characteristic size r_{1*} is assumed (or estimated by theory or observational constraints). From the estimated mass of the black hole, other parameters may be obtained. For example, the accretion rate may be estimated by assuming that the needed γ-rays to power the PPP process in Cen A and 3C 273 are from a π^0 spectrum; the neutral pions arise in the hot, spatially extended, optically thin disk with ion temperatures $T_i \sim 100$ MeV, appropriate for the two-temperature model (see Paper II). Other hot disk models could also be used, although these other models have not been developed sufficiently for γ-ray emission estimates to be made.

Pion production is important for ion temperatures $\gtrsim 10^{12}$ K. The expression for the ion temperature may be found in Shapiro, Lightman, and Eardley (1976) for nonrotating black holes and in Eilek (1979) for canonical Kerr black holes. Calling the size of the region, with ion temperatures $> 10^{12}$ K, r_2, we have from Eilek (1979)

$$r_{2*} \approx 76.5 \dot{M}_1{}^{2/3} M_8{}^{-2/3} (\alpha/0.1)^{-4/3}\,, \qquad (5)$$

where $r_2 \equiv r_{2*} r_g$ and where the electron temperature was assumed to be $\sim 10^9$ K and an average value of 0.63 for the product of numerical factors in Eilek's expression was used in (5).

The direct contribution of π^0 radiation, without Penrose processes, is most important in the range 1–100 MeV. At lower energies, PCS is important, whereas PPP contributes photons up to a few GeV. In what follows, we assume that the major contribution to the emitted γ-rays in the range 1–100 MeV is from a π^0 spectrum.

We parametrize the total luminosity L in terms of L_0, where $L = 6 \times 10^{46}\, L_0$, and the luminosity from the decay of the neutral pions in the hot, inner region $L(\pi^0)$ in terms of $L_0(\pi^0)$, where $L(\pi^0) = 6 \times 10^{46}\, L_0(\pi^0)$. The L's are in ergs s^{-1}.

We further parametrize the accretion rate $\dot{M}$ in terms of $\dot{M}_1$, where $\dot{M} = \dot{M}_1 \times (1\, M_\odot/\mathrm{yr})$. It follows that

$$L_0 = \beta_1 \dot{M}_1\,, \qquad (6)$$

where β_1 was defined in Paper II as the total efficiency of the accretion process.

Following Dahlbacka, Chapline, and Weaver (1974), the maximum of the π^0 curve observed at infinity is given by

$$\nu = \nu_0[(1 - \beta)/(1 + \beta)]^{1/2}(1 - r_g/r)^{1/2}\,, \qquad (7)$$

where $h\nu_0 = 68$ MeV, the rest frame energy of the γ-rays. Using the appropriate value of β ($\equiv v/c$) for 100 MeV protons and assuming that the maximum contribution of the "escape cone" density product in the integral of the computed γ-rays occurs in the ergosphere (cf. Zel'dovich and Novikov 1971), we find $h\nu \approx 20$ MeV. The number of the emitted γ-rays may be computed in analogous fashion to Dahlbacka, Chapline, and Weaver (1974) (here, the limits of integration are different, appropriate for disk accretion around a canonical Kerr hole, and the density is different from the expression used for the spherical accretion case examined by Dahlbacka *et al.*). We use the following expression for the density of particles in the hot, optically thin, spatially thick inner region of the accretion disk (see Paper II)

$$n \sim (\dot{M}_1/M_8{}^2) r_*{}^{-3/2} \alpha^{-1} 2 \times 10^{12}\ \mathrm{cm}^{-3}\,, \qquad (8)$$

where α is the viscosity parameter estimated to be in the range 0.05–1.0 (Shapiro, Lightman, and Eardley 1976) and $r_* = r/r_g$, where r is the radial distance.

From the integrated number of γ-rays and their average energy computed from (6), we find the relationship

$$\dot{M}_1 \sim 1.7(\alpha/0.1)[M_8 L_0(\pi^0)]^{1/2}\,. \qquad (9)$$

Once $\dot{M}_1$ is determined from (8), β_1 is determined from (5).

On the other hand, $\dot{M}_1$ is related to M_8 and α through another relationship: The very existence of a hot, optically thin inner region requires a minimum value of the accretion rate given by

$$\dot{M}_1 \simeq 3.1 \times 10^{-2} (\alpha/0.1)^{-17/32} M_8{}^{31/32} \qquad (10)$$

(see Eardley and Lightman 1975). As long as $\dot{M}_1$ is greater than the value given in (10), a value of r_{3*}

exists, where r_{3*} is the size of the optically thin, inner region, and it should be greater than 3 for a canonical black hole and probably less than a few hundred. On the other hand, given an r_{3*} and an assumed M_8 value, α is determined uniquely by using (9) in the formulae found in Appendix C of Eardley and Lightman (1975).

In order to have a self-consistent model, the three sizes r_{1*}, r_{2*}, and r_{3*} should be related to each other by the relations

$$r_{1*} \gtrsim r_{2*} \quad \text{and} \quad r_{3*} \gtrsim r_{2*} \, . \tag{11}$$

We call r_{0*} the size applicable when the equalities in (11) hold. The absence of γ-γ absorption in the spectra of the three active galaxies under consideration can be utilized to place limits on the various parameters characterizing the black hole and the accretion onto it. We call $E_{\gamma\gamma}$ the energy of the γ-ray photons at which $\tau_{\gamma\gamma} = 1$. For example, $E_{\gamma\gamma}$ is at least 10 MeV for Cen A. For a given $E_{\gamma\gamma}$, the various parameters can be computed as shown in the Appendix. The dependence of r_{0*}, α, and $\dot{M}_1$ on the mass M_8 is given in formulae (A1)–(A3). We note that for a given $E_{\gamma\gamma}$, the computed mass appropriate for the equalities in (11) is the minimum mass. For larger mass, $r_{1*} = r_{2*} < r_{3*}$. Acceptable values would be those which restrict α in the range 0.05–1.0 and M_8 not unacceptably high (not much larger than, say, 100).

In what follows, we use the term "neighborhood" or "vicinity" for the region within a few hundred gravitational radii of the black hole.

It may, of course, turn out that the product $r_{0*}M_8$ is too small, and therefore $\tau_{\gamma\gamma} > 1$ at a particular photon energy; in this case, γ-rays at that energy cannot be coming from the vicinity of the black hole, otherwise γ-γ scattering would bend the spectrum at that energy. These photons would have to be emitted from a region larger in dimensions than the neighborhood of the black hole. We point out that when PPP operates, very high energy γ-rays do not necessarily have to originate near the black hole: The relativistic pairs can carry out that energy and deposit it over larger path lengths (for example, by bremsstrahlung losses over large path lengths).

In Table 1, typical results are shown for Cen A and 3C 273, two candidates for PPP (PCS may also be present, but a PCS cutoff would be masked by the existence of the very hot inner disk and the PPP electron radiation). The NGC 4151 case will be discussed below.

In the first column, the γ-ray energy at which $\tau_{\gamma\gamma} = 1$ is shown. This is varied as a parameter. The observations of Cen A indicate that $E_{\gamma\gamma}$ is at least 10 MeV. This value would permit PPP to operate in both Cen A and 3C 273, and we therefore adopt it as the minimum possible value. In the second column, the mass of the black hole (in $10^8 \, M_\odot$) computed by the method outlined in the Appendix is shown. By setting the three sizes equal to each other (their common value we call r_{0*}) in (11) the value of M_8 is the minimum for the particular value of $E_{\gamma\gamma}$. In column (3), the common value r_{0*} is shown (in gravitational units). In column (4) the value of the viscosity parameter is shown. Note that the values of α do not vary appreciably from case to case. The fifth column gives the accretion rate (in solar masses per year). Parameters r_{0*}, α, and $\dot{M}_1$ are computed from the formulae in the Appendix. In equations (9), (A2), and (A3) we used the values of the luminosities $L(\pi^0) \sim 5 \times 10^{43}$ ergs s^{-1} for Cen A and $L(\pi^0) \sim 5 \times 10^{46}$ ergs s^{-1} for 3C 273. In column (6), the value of the efficiency is given, determined from $\dot{M}_1$ and the total luminosity L, where L was estimated to be 2×10^{44} ergs s^{-1} for Cen A and 2×10^{47} ergs s^{-1} for 3C 273. In column (7) the ratio $\mathscr{R}$ of the luminosity L to the Eddington value L_{Ed} is given (see Paper II). This ratio is defined from the relationship

$$L_0/M_8 = (\mathscr{R}/6)(\sigma_{\text{T}}/\sigma_{\text{es}}) \, , \tag{12}$$

where σ_{T} is the Thomson cross section and σ_{es} is the appropriate electron scattering cross section in the vicinity of the black hole where the majority of the photons are γ-rays (an average photon energy of 20 MeV was used since γ-rays of at least 30 MeV are emitted from the vicinity of the black hole; see below). In the last column the light travel time for the hot, inner region is shown; this may be observable for γ-rays in a few years. Note, however, that this is not the minimum variability time scale in the Penrose quantum theory (see § V).

So far we have assumed that all the observed X-rays with energy E_T given by (2) are emitted from the same region r_{0*} as the γ-rays of energy, corresponding to E_T, $E_{\gamma\gamma}$. If, however, only a fraction f of the soft radiation E_T is emitted within the region r_{0*}, then the parameters tabulated in Table 1 have to be modified. Their dependence on f is given in relations (A4) of the Appendix. For example, if f were 50%, M_8 would be reduced by a factor of 0.36. We expect that for values $E_T \to E_{\gamma\gamma}$, $f \to 1$; for large $E_{\gamma\gamma}$, however (say more than $\sim$100 MeV), f should be small because softer photons are emitted by the cool "standard" disk (Novikov and Thorne 1973) and not in the hot, inner region. Without any further observations, it is pointless to attempt at this point further parameter fitting. There are, however, future observational tests of the Penrose mechanisms outlined in the present work:

a) Detailed observations of the γ-ray spectra of both Cen A and 3C 273 would give estimates of $E_{\gamma\gamma}$, by seeing where the spectrum starts to steepen.

b) Observing the active nuclei simultaneously at X-rays (say 1–100 keV) and γ-rays (say 10–1000 MeV) would give information on their characteristic sizes of emission. If, for example, 10 keV X-rays and 100 MeV γ-rays are observed to have similar time variations, this would indicate that $f \sim 1$.

c) If the spectrum of 3C 273 does not steepen up to the GeV region, this would not mean that the required mass of the black hole is unacceptably high. It would mean that (i) f is small or, more likely,

(ii) the relativistic PPP produced pairs do not radiate appreciably within the region of size r_{0*}.

d) We further note that γ-rays of energy below $\sim$100 MeV are emitted by processes in the hot, inner disk (pion processes) whereas the majority of GeV γ-rays are emitted by the relativistic PPP produced pairs, and not necessarily in the inner disk. It would be interesting to look for variations as a function of time of MeV γ-rays (say 30 MeV) and of GeV γ-rays. If the present scenario is correct, the former should be varying on time scales about equal to or shorter (or much shorter) than the latter but not vice versa.

We now turn to the specific results for Cen A and 3C 273 followed by the PCS case of NGC 4151.

a) *Centaurus A*

The observations of Hall *et al.* (1976) indicate that there is no break up to 10 MeV, and this places a lower limit to the size of the γ-ray emitting region of 1.3×10^{13} cm. It is unlikely that γ-γ pair production would become important just above the maximum observed energy of 10 MeV.

We find that γ-rays as energetic as 500 MeV could be coming from the vicinity of the black hole; in this case, $M_8 \approx 14$ but r_{0*} is ~ 3, the minimum allowed value. Assuming that γ-rays of energy at least as high as 30 MeV are emitted from the vicinity of the black hole ($r_{0*} \sim 11$) so that PPP can operate, yields a value of $M_8 \sim 0.35$; the required value of α in this case is ~ 0.15, a fairly low and acceptable value. It is interesting to note that Fabian *et al.* (1976) obtained a similar mass for Cen A. On the other hand, the rapid variability reported by Delvaille, Epstein, and Schnopper (1978) would argue for a mass not appreciably greater than $M_8 \sim 1$. We note that, for this mass, γ-γ scattering is unimportant below 100 MeV in the vicinity of the black hole. Without any information on temporal variations of the γ-ray intensity from Cen A it is impossible to determine M_8 directly; since limits on the product $M_8 r_{0*}$ are set by the above procedure, variability measurements would give information on this product and therefore would help in the determination of M_8 and r_{0*}. As can be seen, though, from the above discussion and from the results of Table 1, the best estimates of the mass of the black hole in Cen A are in the range 10^7–10^8 $M_\odot$. Gamma rays of at least 100 MeV may be coming from the neighborhood of the black hole. Higher energy γ-rays would be expected to originate in a larger size region (as is the case with 3C 273; see below). However, no matter where high-energy γ-rays are coming from, we expect a steep cutoff at GeV energies—this cutoff is intrinsic to the PPP process. Moreover, the PPP cutoff in the energy of the ejected electrons would cause the γ-ray spectrum to bend in the 1–10 GeV region, whereas the γ-γ pair production process would bend the spectrum in a much more gradual fashion. We have seen that probably, at least up to 30 MeV, this process is unimportant.

b) *3C 273*

No steep break is evident up to at least 500 MeV (Swanenburg *et al.* 1978). We emphasize again that this does not imply an unacceptably high value of M_8. Rather, it implies that either f is small (i.e., that GeV and keV radiation is not emitted in the same region) or, more likely, the PPP relativistic pairs radiate high-energy GeV radiation outside of the immediate neighborhood of the black hole. Time variation observations would be very important. Gamma rays, though, of energy $\sim$10–100 MeV could be emitted from the vicinity of the black hole, permitting PPP to operate efficiently. We indeed find that the values of M_8 in the range 20–50, which are estimates for the mass of the massive black hole in M87 (Young *et al.* 1978; de Vaucouleurs and Nieto 1979) yield reasonable values for the parameters. Efficiencies β_1 in the range 0.06–0.30 would result, larger than the efficiencies for Cen A, and indicating that 3C 273 is an efficient power generator.

c) *NGC 4151*

For this object the preceding analysis cannot be applied, particularly formula (9), since the sharp break at $\sim$2 MeV and the continued drop of the spectrum up to at least 100 MeV indicate that PPP is very weak. We already attributed the MeV break to the PCS process.

We find that the γ-γ pair production process cannot possibly explain the steep break in the MeV region: Since $F \propto E^{-1}$ in (4), the product $E_T F(2E_T)$ is independent of E_T and therefore does not depend on the γ-ray energy E; if γ-γ were to operate above a certain energy, it would also operate below that energy—over a wide range—and no γ-rays would reach us from NGC 4151. We emphasize that this reasoning is independent of any assumptions and follows directly from the observed fact that the photon spectrum follows an E^{-1} law.

We note that the PCS produced break in the γ-ray spectrum of NGC 4151 is sharp, and this agrees with theory: PCS can only operate with electrons, whereas PPP can operate with He nuclei; therefore, the PPP GeV break would probably not be as sharp as the PCS MeV break.

From the lack of γ-γ pair production and assuming a characteristic size $r_{0*} \gtrsim 15$ for the γ-ray emitting region, we find a lower limit to the mass of the black hole of 5×10^7 $M_\odot$. This estimate cannot be too far off: If it were lower, γ-γ would operate; if, on the other hand, the mass is appreciably greater than 10^8 $M_\odot$, the short X-ray variability reported by Mushotzky, Holt, and Serlemitsos (1978) could not be explained.

Following Piran and Shaham (1977*a*), we estimate that $0.05 \lesssim \beta_1 \lesssim 0.4$; therefore, for a total luminosity $L \sim 2 \times 10^{45}$ ergs s^{-1}, the accretion rate is in the range $8.3 \times 10^{-2} \lesssim \dot{M}_1 \lesssim 0.66$. In Table 1 we show the relevant parameters for NGC 4151 if $M_8 \sim 0.5$ and $\beta_1 \sim 0.25$. These values give a luminosity from the inner region in good agreement with the observed luminosity below ~100 keV (cf. Shapiro, Lightman, and Eardley 1976).

V. DISCUSSION AND CONCLUSIONS

The γ-ray observations of Cen A, 3C 273, and NGC 4151 have been used to obtain black hole parameters for these objects under the assumption that they are powered by either PPP (for the first two) or PCS (for NGC 4151). It has been argued that the data indicate no γ-γ pair production (therefore no absorption for the γ-rays), at least below ~30 MeV; for NGC 4151 this statement arises directly from the observations. It is, therefore, plausible that γ-rays up to at least 30 MeV would not get absorbed within the hot, inner region. We note here that even for 3C 273, absorption of high-energy γ-rays (say >100 MeV) would not take place close to the black hole if the softer photons needed for γ-γ scattering (UV and X-ray photons) were not present in this hot, inner region. The lack of absorption of γ-rays below ~30 MeV allows us to construct self-consistent PPP models for Cen A and 3C 273; in these models 10–100 MeV γ-rays from the hot accretion disk (that could be due to a π^0 spectrum for the two-temperature model) enter the ergosphere of a massive, canonical Kerr black hole and produce high-energy electron-positron pairs which escape from the ergosphere after the Penrose process. The PPP process will produce an intrinsic break in the 1–10 GeV region (most likely ~2 GeV) which should show up independently of whether or not γ-γ pair production eventually becomes important at energies above 100 MeV.

For NGC 4151 a sharp break has been observed in the MeV region of the spectrum, and this is attributed to the PCS process. The weakness of the PPP process in NGC 4151 is consistent with the low power in radio waves, since it is the same high-energy PPP ejected pairs which eventually radiate in the radio (presumably farther out). On the other hand, both Cen A and 3C 273 emit appreciably in the radio part of the spectrum. Whether or not the pairs will escape from the (vertically) extended hot, optically thin accretion disk depends on the ratio of the radiation length (due to relativistic bremsstrahlung, inverse Compton, and synchrotron—if magnetic fields are present in the accretion disk) to the quantity $r_{0*}r_g$. Along the axis of rotation, escape would be easy since essentially no radiation is found in that direction close to the black hole. For relativistic bremsstrahlung cooling, this ratio is proportional to $M_8/\dot{M}_1$. Calling η_B, η_C, and η_S the ratios t_B/t_*, t_C/t_*, and t_S/t_*, respectively, where t_B is the relativistic bremsstrahlung loss time scale, t_C the inverse Compton loss time scale, and t_S the synchrotron loss time scale and where $t_* = r_{0*}r_g/c$, we have the following relations for 1 GeV electrons:

$$\eta_B \sim 0.4M_8/\dot{M}_1(r_{0*}/10)^{1/2}\,, \tag{13}$$

$$\eta_C \sim 0.16qM_8/L_0(r_{0*}/10)\,, \tag{14}$$

where $q = 1$, 320, 2.5×10^4 for $h\nu = 500$ keV, 10 MeV, 100 MeV photons interacting with the GeV electrons, and

$$\eta_S \sim 83[H^2M_8(r_{0*}/10)]^{-1}\,, \tag{15}$$

where H is the appropriate magnetic field inside the region of dimensions $r_{0*}r_g$. If any of the η's is smaller than 1, the appropriate losses will be severe for the PPP electrons. We find that, for all cases listed in Table 1, η_B and η_C are greater than 1, the smallest values of the ratios found for NGC 4151.

The magnitude of H inside the hot, inner region is totally unknown. We find that magnetic fields of a few Gauss will result in severe losses for the GeV electrons. Along the axis of rotation, though, the losses are very small. This happens because both η_B and $\eta_S = \infty$ along the rotation axis (since there is no accretion disk in that direction). The only losses would be Compton, and these are the least severe of all (unless, of course, the electrons encounter soft photons, which is unlikely in the vicinity of the black hole; farther out, though, these losses would become important). The pairs ejected along the axis are fewer than those ejected, say, along the equator (see § III). Since, though, they survive more in that direction, PPP has built into it the possibility of contributing to the explanation of the lobes of radio galaxies.

Without detailed information on the γ-ray spectra over a large range of energies and without any information on γ-ray variability, it is impossible to pinpoint better the parameters listed in Table 1. Even with the limited information available, though, it is possible to give ranges of parameters for the three active galaxies. From the discussion in § IV, we found that a likely range for the mass of the black hole in NGC 4151 is $0.3 \lesssim M_8 \lesssim 1$, for Cen A is $0.1 \lesssim M_8 \lesssim 1$, and for 3C 273 is $10 \lesssim M_8 \lesssim 100$, consistent with the mass $M_8 \sim 20$–50 for M87.

We note that the total efficiency for Cen A is less than that for 3C 273 and could be as low as 1%. On the other hand, the efficiency for some of the 3C 273 models could approach 30%. This is, again, consistent with the observable fact that 3C 273 is a more powerful active galaxy than Cen A. The efficiency of a single Penrose process exceeds unity, but the overall efficiency is expected to be lower than that due to the capture of many of the particles by the black hole. Our deduced efficiencies are less than 0.4, the maximum efficiency for a Kerr black hole without Penrose processes. This indicates the importance of the Penrose processes which, even operating at low level, can provide a very luminous source. For NGC 4151 the efficiency was assumed to be ~0.25, in accordance with Piran and Shaham (1977*a*).

The luminosities of 3C 273 and Cen A are well below the Eddington limit. Note that the Eddington luminosity is larger than the usual expression because, for γ-rays, the electron scattering cross section is less than the Thomson value. For 3C 273 the luminosity is less than a few percent of the Eddington value.

A check of self-consistency is provided by computing the optical depths for the Penrose processes for the parameters of Table 1 and see whether the optical depths are reasonable. The optical depths should only be estimated near the black hole, since at large distances the optical depths become negligible due to the rapid decrease of the density. Following the convention of Paper II, we use the index 3 to refer to the region just outside the ergosphere ($2 \lesssim r_* \lesssim 3$) and 1 to refer to the target region ($r_{\text{mb}} \lesssim r \lesssim r_{\text{ms}}$). The density is expected to peak within the ergosphere (Paper II) and therefore $n(1) > n(3)$. Moreover, the optical depth for pair production in region 3 should not be large, otherwise the γ-rays would produce pairs far from the target region and no PPP would occur; this requirement is written as $\tau(3) < 1$. Finally, if $n(1) > n(3)$, the condition $\tau(1) > \tau(3)$ is automatically satisfied; both conditions require that $\lambda(1) < 2\lambda(3)$, where $h = \lambda r$, and h is the half-thickness of the disk. We do not necessarily impose the more stringent condition $\tau(1) > 1$, which, if true, would mean that PPP operates very efficiently.

The expression for $\tau(3)$ is $\tau(3) \sim 4 \times 10^{-2}(\dot{M}_1/M_8) \times \alpha^{-1}\lambda(3)^{-1}$. Typical values calculated from the parameters in Table 1 are, for Cen A, $\tau(3) \sim 0.11$ if $E_{\gamma\gamma} = 10$ MeV, and $\tau(3) \sim 0.02$ if $E_{\gamma\gamma} = 100$ MeV. For 3C 273, $\tau(3) \sim 0.11$ for $E_{\gamma\gamma} = 10$ MeV and $\tau(3) \sim 0.02$ for $E_{\gamma\gamma} = 100$ MeV. Typically, $\tau(1)$ would be a few times greater. The range of values of τ is wide enough to permit the Penrose processes to take place without stringent conditions.

In this paper we mentioned a few possible ways that the observed spectra can be explained. Fitting a single power law through the data and extending it up to the expected Penrose breaks might be an oversimplification; absorption of high-energy (say >100 MeV) γ-rays would gradually bend the spectrum. No matter, though, at what energies γ-γ scattering becomes important, a sharp cutoff is expected in the GeV region for Cen A and 3C 273. For objects like Cen A which are highly variable, it would be extremely important to have simultaneous observations at X-rays and γ-rays to try to determine the characteristic sizes of the regions and therefore the radiation mechanisms responsible.

The Penrose processes discussed in this paper cannot operate unless the black hole is spinning rapidly. For example, if $a/M = 0.95$ and if $T_e \sim 10^9$ K, the maximal energy of the ejected γ-rays in the PCS process is $m_e c^2$ (see Piran and Shaham 1977*b*). The Penrose processes, draining energy from the black hole, will eventually slow it down to the point that these processes will no longer operate. We point out, though, that it is not entirely clear how the combined effects of accretion and Penrose processes will affect the spin as a function of time. Thorne's (1974) calculations should be generalized. We can estimate, however, a rough value for the lifetime of Penrose processes since in Penrose processes a good portion of the emitted luminous power is derived from the rotational energy of the black hole which is estimated as 4×10^{61} M_8 ergs. The rotational lifetime is $t_R \sim (M_8/L_0)2 \times 10^7$ yr.

The effective lifetime for the Penrose processes should be less than t_R since when the spin has slowed down to values below $a/M \sim 0.95$, the efficiency of the Penrose processes drops down dramatically; for $a/M < 0.9$ the target region is found outside the ergosphere (Bardeen, Press, and Teukolsky 1972). Energy will, of course, continue to be radiated away even without the Penrose processes, but one would not expect, for example, a strong radio source or a strong γ-ray source. The effect of "aging" for the spin of the black hole would be most dramatic in the absence of relativistic electrons and γ-rays above ~ 1 MeV. X-rays, however, and less energetic photons emitted by thermal processes would still be emitted.

Small black holes would age faster than massive ones (because they have less available rotational energy) if they were radiating comparable amounts of energy. We expect PPP to shut off first because it requires high-energy photons and these photons would cease to be emitted in the inner, hot disk as the angular momentum density drops. On the other hand, PCS would be expected to last longer since it requires softer photons. Moreover, the γ-γ scattering process is most important for smaller-mass black holes, and this effect would deplete high energy γ-rays. The absence of PPP in NGC 4151 may be due to the specific accretion scenario. The evolutionary effect of the spin-down of the black hole may explain the contribution of objects like NGC 4151 to the γ-ray background (Bignami, Lichti, and Paul 1978): Maybe only 1% of all Seyferts radiate in the same manner as NGC 4151. Seyferts would radiate as long as the accretion process continues—in other words, as long as there is infalling matter—however, only the rapidly spinning black holes would produce an MeV γ-ray emitting Seyfert (through the PCS process). Similarly, we expect a small percentage of all giant elliptical galaxies to be emitting both radio synchrotron radiation and high-energy γ-rays. There should be a direct correlation between strong radio sources and γ-ray sources (leaving aside the question of orientation of the observer with respect to the axis of rotation).

We point out that there are many instabilities associated with the accretion disk around a black hole; a natural time scale, though, to consider is the light travel time through the target region where the Penrose processes take place. This is estimated to be $\sim 8000 M_8$ s (Paper I). We expect this characteristic time scale to show up at all wavelengths, since in a Penrose scenario the electrons which are responsible for the radiation processes at different parts of the spectrum have their origin in the target region. From the discussion in § IV it follows that it would be extremely important to have detailed γ-ray observations for energies in the range 1 MeV to a few GeV. These observations would give information on the energies at which the γ-γ pair production begins to become important and would therefore provide a handle on the various parameters. Observations of temporal variations would also provide independent information as outlined before; for this we distinguish three spectral regions of interest: the X-ray region (1–100 keV) which scatters the higher energy γ-rays; γ-rays emitted by the hot inner region (1–100 MeV); and γ-rays that originate in the radiation of the relativistic PPP produced pairs ($\gtrsim 100$ MeV to a few GeV).

All these questions can only be answered by a combination of observational and further theoretical work. It is particularly important that more active galaxies be detected at γ-rays, that possible γ-ray variability be established, and that simultaneous observations at X-rays and γ-rays be obtained. A particularly attractive situation would be the observations of active galaxies with the *HEAO 2* (*Einstein*) and *GRO* satellites.

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APPENDIX

BLACK HOLE PARAMETERS

We show here how the various parameters in Table 1 are obtained. The characteristic sizes r_{1*}, r_{2*}, and r_{3*} of § IV are related to each other by relations (11). For a particular $E_{\gamma\gamma}$ and when all of them are equal to each other, the value of M_8 obtained is the minimum value. We call r_{0*} their common value. Setting $\tau_{\gamma\gamma} = 1$, we have from (4)

$$r_{0*} = BfM_8^{-1}\,, \tag{A1}$$

where $B = D^2_{\rm Mpc} 9E_T({\rm keV})F(2E_T)$ and is a function of $E_{\gamma\gamma}$, and where f is the fraction of radiation E_T emitted within r_{0*}. Setting r_{0*} equal to r_{2*} from (5), we solve for $\dot{M}_1$ in terms of M_8, Bf, and α. We then equate the expression found to relationship (9) and solve for α. The resultant expressions are

$$\alpha = 1.14 \times 10^2 M_8[L_0(\pi_0)]^{1/2}\{Bf\}^{-3/2} \tag{A2}$$

and

$$\dot{M}_1 = 1.94 \times 10^3 M_8^{3/2} L_0(\pi_0)\{Bf\}^{-3/2}\,. \tag{A3}$$

The value of M_8 for the particular $E_{\gamma\gamma}$ value is obtained by solving equation (C4) of Appendix C in Eardley and Lightman (1975) and finding the extent of the optically thin region r_{0*}. If this value agrees with (A1), the procedure is finished; otherwise a different value of M_8 is guessed.

If all the observed X-rays of energy E_T are not emitted in the same region of size r_{0*} as the γ-rays of energy $E_{\gamma\gamma}$, the computed parameters have to be modified. Limits on f could be placed by future observations. The various parameters depend on f as follows:

$$M_8 \propto f^{25/17}\,, \quad r_{0*} \propto f^{-8/17}\,, \quad \alpha \propto f^{-1/34}\,, \quad \dot{M}_1 \propto f^{24/34}\,,$$
$$\beta_1 \propto f^{-24/34}\,, \quad \mathscr{R} \propto f^{-25/17}\,, \quad (r_{0*}r_g)/c \propto f\,. \tag{A4}$$

REFERENCES

Bardeen, J. M., Press, W. H., and Teukolsky, S. A. 1972, *Ap. J.*, **178**, 347.
Beall, J. H., *et al.* 1978, *Ap. J.*, **219**, 836.
Bignami, G. F., Fichtel, C. E., Hartman, R. C., and Thompson, D. J. 1979, preprint.
Bignami, G. F., Lichti, G. G., and Paul, J. A. 1978, *Astr. Ap. Letters*, **68**, L15.
Bisnovatyi-Kogan, G. S., and Blinnikov, S. I. 1976, *Soviet Astr. Letters*, **2**, 191.
Cavallo, G., and Rees, M. J. 1978, *M.N.R.A.S.*, **183**, 359.
Culhane, J. L. 1978, *Q.J.R.A.S.*, **19**, 1.
Cunningham, C. T. 1975, *Ap. J.*, **202**, 788.
Dahlbacka, G. H., Chapline, G. F., and Weaver, T. A. 1974, *Nature*, **250**, 36.
Delvaille, J. P., Epstein, A., and Schnopper, H. W. 1978, *Ap. J.* (*Letters*), **219**, L81.
de Vaucouleurs, G., and Nieto, J. L. 1979, *Bull. AAS*, **10**, 629.
Eardley, D. M., and Lightman, A. P. 1975, *Ap. J.*, **200**, 187.
Eardley, D. M., Lightman, A. P., Payne, D. G., and Shapiro, S. L. 1978, *Ap. J.*, **224**, 53.
Eilek, J. A. 1979, preprint.
Fabian, A. C., Maccagni, D., Rees, M. J., and Stoeger, W. R. 1976, *Nature*, **260**, 683.
Grindlay, J. E., Helmken, H. F., Hanbury Brown, R., Davis, J., and Allen, L. R. 1975, *Ap. J.* (*Letters*), **197**, L9.
Gursky, H., and Schwartz, D. A. 1977, *Ann. Rev. Astr. Ap.*, **15**, 541.
Hall, R. D., Meegan, C. A., Walraven, G. D., Djuth, F. T., and Haymes, R. C. 1976, *Ap. J.*, **210**, 631.
Helmken, H. F., and Weeks, T. 1978, San Diego X-Ray and Gamma Ray Astronomy Meeting, Sept.
Herterich, K. 1974, *Nature*, **250**, 311.
Jelley, J. V. 1966*a*, *Nature*, **211**, 472.
———. 1966*b*, *Phys. Rev. Letters*, **16**, 479.
Kafatos, M., and Leiter, D. 1979, *Ap. J.*, **229**, 46 (Paper II).
Katz, J. I. 1976, *Ap. J.*, **206**, 910.
Leiter, D., and Kafatos, M. 1978, *Ap. J.*, **226**, 32 (Paper I).
———. 1979, in *Proceedings of La Jolla Institute Workshop on Particle Acceleration Mechanisms in Astrophysics* (American Institute of Physics).
Liang, E. P. T., and Price, R. H. 1977, *Ap. J.*, **218**, 247.
Lightman, A. P., Giacconi, R., and Tananbaum, H. 1978, *Ap. J.*, **224**, 375.
McBreen, B. 1979, preprint.
Mushotzky, R. F., Holt, S. S., and Serlemitsos, P. J. 1978, *Ap. J.* (*Letters*), **225**, L115.
Novikov, I. D., and Thorne, K. S. 1973, in *Black Holes*, ed. DeWitt and DeWitt (New York: Gordon & Breach).
Payne, D. G., and Eardley, D. M. 1977, *Ap. Letters*, **19**, 39.
Piran, T., and Shaham, J. 1977*a*, *Ap. J.*, **214**, 268.

Piran, T., and Shaham, J. 1977*b*, *Phys. Rev. D*, **16**, 1615.
Pollack, J. B., Guthrie, P. D., and Shen, B. S. P. 1971, *Ap. J. (Letters)*, **169**, L113.
Pringle, J. E., Rees, M. J., and Pacholczyk, A. G. 1973, *Astr. Ap.*, **29**, 179.
Rees, M. J. 1978, *Phys. Scripta*, **17**, 193.
Schönfelder, V. 1978, *Nature*, **274**, 344.
Shakura, N. I., and Sunyaev, R. A. 1973, *Astr. Ap.*, **24**, 337.
Shapiro, S. L. 1974, *Ap. J.*, **189**, 343.
Shapiro, S. L., Lightman, A. P., and Eardley, D. M. 1976, *Ap. J.*, **204**, 187.
Stark, J. P., Davison, P. J. N., and Culhane, J. L. 1976, *M.N.R.A.S.*, **174**, 35.
Swanenburg, B. N., *et al.* 1978, *Nature*, **275**, 298.
Thorne, K. S. 1974, *Ap. J.*, **191**, 507.
Young, P. J., Westphal, J. A., Kristian, J., and Wilson, C. P. 1978, *Ap. J.*, **221**, 721.
Zanrosso, E. M., *et al.* 1979, preprint.
Zel'dovich, Y. B., and Novikov, I. D. 1971, *Relativistic Astrophysics* (Chicago: University of Chicago Press).

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