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HIGH-ENERGY RADIATION FROM ACTIVE GALACTIC NUCLEI

MAREK SIKORA
N. Copernicus Astronomical Center, Polish Academy of Sciences, Warsaw, Poland, and Joint Institute for Laboratory Astrophysics,
University of Colorado and National Institute of Standards and Technology, Boulder, Colorado

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ABSTRACT

Two recent findings concerning high-energy radiation properties of active galactic nuclei—discovery of breaks in hard X-ray spectra of Seyfert galaxies, and discovery of huge fluxes of hard gamma rays from blazars—seem to press us to change our standard views about radiation production in these objects. I review briefly the existing radiation models, confront them with the newest observations, and discuss newly emerging theoretical pictures which attempt to account for the discoveries.

Subject headings: galaxies: active — galaxies: nuclei — radiation mechanisms: nonthermal

1. INTRODUCTION

Typical active galactic nuclei (AGNs) are known to emit the bulk of their energy across a spectral range covering seven decades of photon energy, from the far-infrared to hard X-rays. One can distinguish three characteristic spectral components: an infrared component, which peaks in the range 3×10^{13}–3×10^{14} Hz and has a sharp cutoff at $\simeq 3 \times 10^{14}$ Hz (Edelson & Malkan 1986; Kriss 1988; Sanders et al. 1989; Barvainis 1990); the UV bump, which often extends up to soft X-rays (Malkan & Sargent 1982; Bechtold et al. 1987; Laor 1990); and a power-law X-ray spectrum (Rothschild et al. 1983; Turner & Pounds 1989; Pounds et al. 1990). The UV radiation has a natural interpretation, as thermal emission of an optically thick accretion disk (Shields 1978). The IR component is probably produced by reprocessing of UV radiation by dust located at distances > 1 pc (Barvainis 1987; Phinney 1989; Pier & Krolik 1992; Loska, Szczerba, & Czerny 1993), whereas the X-ray spectrum must originate in a rarefield, very hot plasma, possibly including a relativistic component. Part of the X-ray radiation is absorbed by the disk and reemitted in the UV range, competing there with viscously generated radiation (Ulrich 1991; Clavel et al. 1992). Additional contribution to the UV radiation can come from optically thin clouds (Antonucci & Barvainis 1988).

Observations of short time scale, high-amplitude X-ray variability convince us that most of the X-ray production is taking place in the very central parts of the accretion flow (McHardy 1988), possibly in an accretion disk corona powered by magnetic flares (Galeev, Rosner, & Vaiana 1979). As of now there is no consensus about the mechanism of X-ray production. The power-law X-ray spectra can be formed in several ways: by thermal or nonthermal inverse Compton process, by synchrotron radiation, and by saturated pair cascades. In thermal Compton models the power-law spectra result from the superposition of many components representing different orders of scatterings of soft photons. The resulting spectral slope depends sensitively on the combination of temperature and Thomson optical thickness of the source (Katz 1976; Sunyaev & Titarchuk 1980). In nonthermal Compton models the power-law spectra can result from just first-order scattering, provided that the electrons are injected with a power-law energy distribution (Blumenthal & Gould 1970). However, if the luminosity of injected electrons is higher than the luminosity of the background soft radiation field (the condition of "photon starvation"), then higher order scatterings become important and the spectral slope depends on the ratio of these luminosities (Zdziarski, Coppi, & Lamb 1990). The synchrotron radiation spectrum always reflects the electron spectrum (Ginzburg & Syrovatsky 1969), and therefore has a power-law shape for a power-law electron energy distribution. Finally, pair production can be involved in any or all of the above processes. In a purely thermal model pair production controls the maximum electron temperature and, therefore, limits the extension of the spectrum to high energies (Svensson 1990). In the case of nonthermal processes pair production can determine the overall spectral shape. In particular, saturated pair cascades produce spectra with slopes $\alpha \simeq 1$ (Svensson 1987).

All of the above possibilities will be discussed in § 2 in the context of data from *Ginga,* Sigma, and OSSE. Two results from the data should be stressed:

X-ray spectra of many AGNs harden at $E \gtrsim 15$ keV and show prominent fluorescent iron lines at $\simeq 6.4$ keV (Pounds et al. 1990; Williams et al. 1992). These features were predicted by Guilbert & Rees (1988) and Lightman & White (1988) to result from scattering and reprocessing of X-rays from optically thick matter;

X-ray spectra of several AGNs are found to steepen around 100–200 keV (Jourdain et al. 1992; Cameron et al. 1993; Maisack et al. 1993) and, as of now, no annihilation line or gamma-ray tails have been detected in nonblazar AGNs.

Many AGNs produce not only radiation but also jets—narrow streams of plasma—which power extended double radio structures (Begelman, Blandford, & Rees 1984). The luminosities of these structures do not correlate well with the bolometric luminosities of AGNs. The extended radio luminosities L_R are quite low in most quasars ($L_R \ll 0.01 L_{\rm bol}$) and in Seyfert galaxies (spiral galaxies whose nuclei resemble less luminous versions of quasars). However, L_R is high in some small fraction of quasars, and in some elliptical galaxies which show only marginal signatures of central activity. The latter are called radio galaxies and are divided into two types: FR 2–type radio galaxies, which have edge-brightened double radio structures, and FR 1–type radio galaxies, which have edge-darkened double radio structures (Fanaroff & Riley 1974). FR 2 radio galaxies are on average more luminous than FR 1 radio galaxies.

Jets are resolved by VLBI (Very Long Baseline Interferometry) down to parsec scales and are believed to be powered by the rotating black hole (Blandford & Znajek 1977) and/or the accretion disk (Blandford & Payne 1982). That they are accelerated up to relativistic speeds is documented by observations of "superluminal velocity" effects (Porcas 1987), which were predicted by Rees in 1966, and by the peculiar properties of OVV (Optically Violently Variable) quasars and BL Lac objects, which together make up the subclass of objects called blazars (Blandford & Rees 1978).

Radiation of blazars in the radio-UV range is well-represented by a single smooth component, is strongly variable, and, except at radio frequencies, is highly polarized (Impey & Neugebauer 1988; Angel & Stockman 1985). BL Lac objects differ from OVV quasars mainly by the lack of any prominent emission lines. The radiation properties of blazars are naturally interpreted as a result of the Doppler beaming of synchrotron radiation produced in relativistic jets closely aligned with the line of sight (Blandford & Königl 1979). Such an interpretation is strongly supported by the core-halo or core-jet radio morphology of blazars (Antonucci & Ulvestad 1985). Detailed statistical analyses show that the parent objects of OVV quasars are radio-loud quasars, whereas BL Lac objects belong to FR 1 radio galaxies (Padovani & Urry 1992). In this unification scheme FR 2 radio galaxies are considered to be radio-loud quasars which are oriented edge-on, and whose nuclei are therefore hidden by dust (Barthel 1989).

Blazars, like other AGNs, are also X-ray emitters (Worrall et al. 1987; Worrall & Wilkes 1990). In most BL Lac objects the X-ray fluxes lie on an extrapolation of the UV spectrum and, therefore, are probably of synchrotron origin. However, a hardening of the X-ray spectrum at higher energies, seen in some BL Lac objects and more often in OVV quasars, suggests the presence of a second radiation component in blazars. This additional component is especially evident in OVV quasars, where the X-ray fluxes often lie well above the extrapolated UV spectra and have a much harder spectrum (Kii et al. 1992).

As was discovered recently by EGRET (Hartman et al. 1992; Fichtel et al. 1993), the hard X-ray spectra in blazars are just tiny portions of huge radiation components, which extend up to GeV energies and often are much more luminous than the lower energy components. Possible gamma-ray production scenarios include: Comptonization of synchrotron radiation by relativistic electrons/positrons in mildly relativistic ($\Gamma_j \sim 10$) jets (synchrotron-self-Compton models: Maraschi, Ghisellini, & Celotti 1992; Marscher & Bloom 1992); Comptonization of external radiation by relativistic electrons/positrons in mildly relativistic jets (Dermer, Schlickeiser, & Mastichiadis 1992; Zbyszewska 1993; Blandford 1993; Sikora, Begelman, & Rees 1993, 1994); Comptonization of external radiation by cold electrons in ultrarelativistic ($\Gamma_j > 10^4$) jets (Coppi, Kartje, & Königl 1993); and synchrotron radiation of extremely relativistic electrons/positrons injected by ultrarelativistic protons in mildly relativistic jets (Mannheim & Biermann 1992). We discuss these scenarios in § 3.

2. PRODUCTION OF X-RAY RADIATION IN AGNs

2.1. *Thermal Compton Models*

As was shown by Katz (1976) and Shapiro, Lightman, & Eardley (1976), unsaturated multiple Compton scattering of soft photons in a hot thermal plasma leads to the production of roughly a power-law spectrum. Shapiro et al. used these results to explain the power-law X-ray spectrum of Cygnus X-1. In order to get a very hot and optically thin plasma they adopted the two-temperature accretion scenario proposed by Thorne & Price (1975). In this scenario the innermost, radiation pressure–supported part of the standard accretion disk is blown up due to thermal and viscous instabilities (Pringle, Rees, & Pacholczyk 1973; Lightman & Eardley 1974) and an optically thin ion pressure–supported torus is formed provided that ions are coupled to the electrons only via Coulomb interactions. This model, first applied to AGNs by Liang & Thompson (1979), was developed in the 1980s by including bremsstrahlung and thermal cyclotron/synchrotron radiation processes as additional sources of soft photons, and by taking into account radiative and dynamical effects of the pair production process (see Svensson 1990 and references therein).

Two-temperature disk models, however, face two serious difficulties: first, unreasonably fine tuning of the hot thermal plasma temperature and density is required to obtain the correct spectral slope with the observed small spread in spectral indices; and second, the fraction of X-rays intercepted by the external, optically thick part of the accretion disk is too low to explain the observed effects of X-ray reflection by the cold matter. Consequently, the most promising thermal models are those in which the X-rays are produced in an accretion disk corona. The disk-corona configuration was originally considered by Liang & Price (1977) to explain the radiation from Cygnus X-1, and recalculated for AGN environments by Liang & Thompson (1979). A fully self-consistent treatment of the disk-corona model, including pair production and reflection effects, was recently provided by Haardt & Maraschi (1991). They showed that in the scenario where most gravitational energy is released in the disk corona, the slope of the thermal Compton spectrum is stabilized at $\alpha \simeq 1$ and hardened a little at photon energies > 15 keV. The frequently observed flatter spectra can be obtained in the model if the disk is covered only partially by the corona. Partial covering also allows one to avoid smearing out the fluorescent iron lines by Comptonization in the corona, and to obtain higher ratios of the UV flux to the soft X-ray flux.

In its original version, the model is not able to reproduce the inequality $L_{\rm UV} > L_{\rm X}$, which is evidently satisfied in most AGNs. The problem can be overcome by assuming that the magnetic flare activity is proportional to the gas pressure rather than to the total pressure (Sakimoto & Coroniti 1981). In this case coronal activity would be relatively weaker closer to the black hole, where radiation pressure dominates strongly over the gas pressure. As a result, most of the gravitational energy would be released deeply in the optically thick disk.

2.2. *Nonthermal Compton Models*

If most energy dissipated in the disk corona is used to accelerate particles up to relativistic energies, then the production of high-energy radiation can be dominated by Comptonization of the UV bump by relativistic electrons/positrons. They can be accelerated directly, for example, in electric fields generated by reconnection of magnetic fields, and/or injected by relativistic protons following collisions with background thermal protons (Kazanas & Ellison 1986; Zdziarski 1986) and photons (Sikora et al. 1987). The protons, like electrons, can be accelerated in electric fields or, more probably, at strong shocks via the first-order Fermi mechanism (see, e.g., Ellison & Eichler 1984; Blandford & Eichler 1987).

Population of relativistic electrons/positrons can be enriched dramatically if pair cascades occur. As was argued by Guilbert, Fabian, & Rees (1983), the pair cascades can develop naturally in very compact radiation sources and can lead to the formation of power-law X-ray spectra with the spectral index $\alpha \sim 1$. The work by Guilbert et al. was followed by many more detailed studies (Kazanas 1984; Zdziarski & Lightman 1985; Fabian et al. 1986; Svensson 1987); the most complete model, which includes reflection effects from a cold accretion disk, was elaborated by Zdziarski et al. (1990). The latter successfully explained the spectra of many Seyfert galaxies observed by *Ginga* in the energy range 0.5–20 keV (Pounds et al. 1990).

However, the critical observations by which the pair cascade model can be verified are those at energies above a few tens of keV. There the pair cascade model predicts: steepening of the continuum due to downscattering of hard X-ray photons by thermal pairs; production of an annihilation line; and strong depression of the gamma-ray tail by photon-photon pair production. The steepening of AGN spectra at hard X-ray energies was confirmed recently by Sigma/*GRANAT* (Jourdain et al. 1992) and OSSE/*CGRO* (Cameron et al. 1993; Maisack et al. 1993) in observations of several Seyfert galaxies, but the observed breaks are at somewhat higher energies and are much sharper than predicted. Also, no annihilation feature nor gamma-ray tail was noted. Stern et al. (1993) found that the nonthermal pair cascade model can "survive" confrontations with the OSSE observations only if the cooled pairs are kept at much higher temperature than the inverse Compton equilibrium temperature. This requires that the dominant fraction of energy dissipated in the corona be used to heat the pairs.

Another possibility is that electrons/positrons are injected with maximum energies corresponding to the extension of the first-order Compton component up to ~100 keV. This scenario could correspond to the pair reacceleration process studied by Done, Ghisellini, & Fabian (1990).

2.3. *Synchrotron Models*

Synchrotron radiation can be competitive with the Compton process, especially at the sites of magnetic flares. If this process dominates energy loss by electrons/positrons, two very different scenarios emerge depending on whether the electrons/positrons are accelerated directly or injected by relativistic protons. In the former case, the maximum electron/positron energies are determined by the balance of their acceleration rate with their synchrotron cooling rate, and the maximum energy of synchrotron photons is then limited to the value $\eta m_e c^2/\alpha_f \simeq 70\eta$ MeV (Phinney 1983), where $\eta < 1$ is the acceleration efficiency and $\alpha_f = 1/137$. It is easy to check that even for the highest efficiencies the radiation of pairs injected by gamma-ray absorption will not contribute to the X-ray range. Thus, the X-ray spectrum will be produced by directly accelerated electrons/positrons, its slope will be directly related to the injection slope, and the high-energy break for compact objects is expected to be min [70η, few] MeV. No mechanism are known for stabilizing this energy at ~100 keV or for fine-tuning conditions in the background thermal plasma to provide a break around this energy due to Compton downscattering.

In hadronic models electrons/positrons can be injected with such high energies that a saturated synchrotron pair cascade can develop (Sikora et al. 1987). Here, basic properties of the emerging electromagnetic spectrum are expected to be similar to those obtained in Compton-supported, purely electromagnetic pair cascades (Stern, Sikora, & Svensson 1992). The hadronic model, however, seems to be more attractive than the purely electromagnetic one for two reasons: first, pair cascades in a hadronic model can develop in magnetically dominated regions (e.g., in flares), whereas purely electromagnetic models can develop only in radiatively dominated regions; and second, the hadronic model provides a mechanism to power winds which can ultimately carry clouds producing the broad absorption lines observed in quasars (Weymann, Turnshek, & Christiansen 1985; Begelman, de Kool, & Sikora 1991). The latter can be done by relativistic neutrons produced in the central region by relativistic protons in photomeson reactions and nuclear collisions (Biermann & Strittmatter 1987; Sikora, Begelman, & Rudak 1989) and by photodisintegration of helium (Sikora & Begelman 1992). A large fraction of these neutrons can escape from the central source, and those with energies > 10^5 GeV reach distances > 1 pc before decaying into protons (Eichler & Wiita 1978; Sikora et al. 1989; Kirk & Mastichiadis 1989; Begelman, Rudak, & Sikora 1990). The resulting protons cannot freely escape, even from such distances, because they are magnetically coupled to the background plasma. They deposit energy and momentum to the plasma via Fermi scatterings and by generation of Alfv́en waves. Plasma is then heated, providing better cloud confinement, and is accelerated up to velocities corresponding to the broad absorption line widths, that is, $\sim 0.1c$.

3. RADIATION PROCESSES IN BLAZARS

The same electrons which produce synchrotron radiation also scatter synchrotron photons up to X-ray and gamma-ray energies. This so-called synchrotron–self-Compton (SSC) process was considered to explain the high-energy spectra of blazars by Maraschi et al. (1992) and by Marscher & Bloom (1992). They found that the gamma-ray spectra cannot be reproduced within a one-component homogeneous model, however, even using higher-order Compton components. According to Maraschi et al. it can be done by using the inhomogeneous jet model worked out by Ghisellini & Maraschi (1989) to explain spectral and variability properties of blazars in the radio–to–X-ray range. In this model the jet is assumed to be continuously accelerated, and all jet properties are parameterized by power-law functions of the distance from the black hole. The model was specified for the brightest gamma-ray blazar, 3C 279. In this object, as in several others observed by EGRET, the gamma-ray spectrum is a power law with a spectral index $\alpha \sim 1$, extends up to at least a few GeV, and has a low-energy break detected by COMPTEL at around 10 MeV

(Hermsen et al. 1993). In the Ghisellini et al. scenario, the gamma-ray spectrum is composed from the high-energy parts of synchrotron–self-Compton spectra produced over some range of radii and having higher maximum energies at lower distances. In this, as in any other version of the SSC model, the synchrotron–self-Compton component can dominate over the synchrotron component only if the radiation energy density dominates the magnetic energy density. This means that in the steady state case, the Poynting flux of the jet is too low to provide energy at the rate of radiation losses. The jet must then radiate at the expense of the bulk kinetic energy and, therefore, be decelerated contrary to the model assumption.

Another frailty of SSC models adopted for blazars is that they do not take into account the presence of external radiation fields, which are known from nonblazar AGNs to be very dense in the subparsec regions of AGNs. This issue was raised by Dermer et al. (1992), who suggested that gamma-ray radiation of relativistic electrons/positrons in the jet can be dominated by Comptonization of radiation from the accretion disk rather than by the SSC process (see also Zbyszewska 1993). Then, Blandford (1993) and Sikora et al. (1993, 1994) pointed out that a much stronger effect is provided by the diffuse component of the external radiation field. Such a component is expected from reprocessing and scattering of a fraction of the disk radiation by emission line clouds and intercloud hot plasma. The energy density of the diffuse radiation, $u_{\rm diff}$, is $\sim\Gamma_j^2$ times larger in the comoving frame of the jet than in the black hole frame, whereas the energy density of the magnetic field, u_B, is Γ^2 times lower in the jet comoving frame than in the black hole frame. Hence, denoting by τ the fraction of the disk radiation which is diffused over the distances reaching the most active parts of the jet, we find that the ratio of the luminosity of Comptonized diffuse radiation, L_C, to the luminosity of the synchrotron radiation, L_S, scales with $\tau\Gamma^4(u_{\rm diff}/u_B)$, and can easily exceed one for typical conditions in AGNs. In this model the condition $L_C/L_S > 1$ does not imply $u_{\rm rad} > u_B$, hence the jet need not be decelerated.

There are some differences between the scenario suggested by Blandford and the one proposed by Sikora et al. Blandford suggests that the overall hard gamma-ray spectra results from the superposition of radiation components produced at different distances, each of which has its high-energy cutoff determined by gamma-ray absorption due to pair production. Since the opacity for pair production decreases with increasing distance, in his model the highest energy gamma rays are produced at the largest distances, contrary to the predictions by Maraschi et al. (1992).

Sikora et al. showed that gamma-ray spectra like the one observed in 3C 279 can be reproduced within a one-component model. Pair production is not involved, and the spectral slope is determined by the slope of electron injection function. The break between the gamma-ray and X-ray portions of the spectrum is explained as a result of the inefficient radiative cooling of electrons below a certain energy. The model does not exclude an inhomogeneous or radially stratified distribution of radiating plasma in the jet. In particular, it is proposed that the softer parts of the X-ray spectrum are produced closer to the black hole.

Scenarios in which gamma rays are produced by Comptonization of the diffuse UV radiation field must be modified to explain objects with spectra extending up to >100 GeV, because such gamma rays are absorbed by UV photons. Therefore, the discovery of ~TeV gamma rays from Mrk 421 (Punch et al. 1992) (an object which has also been observed at lower energies by Egret; Lin et al. 1992) suggests that in this object the diffuse UV energy density in the high-energy emission region is relatively weak, and that TeV radiation is produced by Comptonization of infrared radiation or by the SSC process. In the latter case, the SSC component must dominate over the synchrotron component or must be produced in a separate region to avoid the depression of the spectrum by the Klein-Nishina effect (Zdziarski & Krolik 1993). In Mrk 421 the luminosities of the synchrotron and gamma-ray components are similar. Therefore, the lack of a depression in the spectrum at TeV energies means that if an SSC model applies, the dominant portion of the synchrotron radiation cannot be produced in the same region as TeV radiation.

Spectral depression due to the Klein-Nishina effect poses no problem for a model invoking Comptonization of external radiation, provided that the diffuse IR component dominates over the diffuse UV component in the region where the high-energy photons are produced. However, Mrk 421 is a BL Lac object and, like other BL Lac objects and FR 1 radio galaxies, does not show any signatures of UV or IR thermal radiation. The question of whether the observationally imposed upper limits on thermal IR radiation from dust allow this radiation to dominate the cooling of relativistic electrons in a relativistic jet is now under investigation by my collaborators and me.

Two other gamma-ray production models, which also involve relativistic jets as a carrier of radiating plasma, are the "hadronic" model proposed by Mannheim & Biermann (1992), in which an extremely relativistic population of electrons/positrons is injected by relativistic protons, and the "bulk Compton" model proposed by Coppi et al. (1993), in which the gamma-ray spectrum is produced by Comptonization of accretion disk radiation by cold electrons/positrons in the ultrarelativistic jet.

Mannheim & Biermann (1992) proposed that electrons/positrons are injected following photomeson reactions. Such a process in blazars, where the compactness of the radiation field is strongly limited by the transparency of the field for GeV or higher energy photons, can be efficient only for protons with energies > 10^8 GeV. Electrons and positrons injected by these protons have such high energies that a pair cascade must be involved. For this mode of pair injection, it is only the third generation of particles which produces synchrotron radiation in the observable range. I can see several problems with this model. First, very fine tuning is required in order to obtain a third generation radiation component in the right energy range. Second, it is impossible to reproduce an X-ray spectrum as hard as $\alpha < 0.75$ by a third generation of photons for any initial proton injection spectrum. Third, the authors did not take into account the proton-photon pair production process, claiming that photomeson production dominates strongly. However, if one takes into account that the spectral slope of the observed IR radiation (the target for relativistic protons) is not far from the value $\alpha \sim 1$, at which both processes are equally efficient (Sikora et al. 1987), and that about half of the proton energy lost in photomeson production is converted to neutrinos, then one finds that the radiation contribution from proton-photon pair production is not negligible, and can smear out the radiation "gap" observed between the UV and gamma-ray bands.

In the model proposed by Coppi et al. (1993), the jet starts with an extremely high bulk Lorentz factor, $\Gamma_j > 10^4$, and is decelerated by interacting with the disk radiation field. For such a scenario a random relativistic component is not required, and Comptonization of the UV radiation up to GeV energies can be done by cold electrons ordered in the ultrarelativistic bulk flow. The model requires an extremely efficient mechanism of jet acceleration which, in principle, could be provided by electric fields generated by unipolar induction involving a spinning supermassive black hole (Michel 1987). However, it is not clear if any significant electrical gap can be created in the dense environment surrounding a supermassive black hole in an AGN, since the electrically mobile and dense plasma will effectively cancel any electric field component along magnetic field lines. Another problem with the model is that ultrarelativistic jets will be decelerated down to $\Gamma_j \sim 10$ very close to the black hole, and, therefore, the gamma-rays will be produced in a very compact central region. They cannot escape such a region, unless there is no external X-ray radiation.

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