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# MULTIFREQUENCY EMISSION FROM HOT ION DISKS

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## ABSTRACT

The discovery of a large number of $\gamma$-emitting active galactic nuclei (AGNs) by the EGRET instrument on the *Compton Gamma Ray Observatory* (*CGRO*) has spawned a lot of theoretical interest in the high-energy and multifrequency emission from these objects. Since most of them show evidence for relativistic outflow, jet models have received most of the attention so far. However, the presence of soft photons at the center of the active nucleus and the resulting Compton drag make it difficult to produce the observed amount of MeV/GeV emission.

We explore hot, two-temperature accretion disks around Kerr black holes as an alternative to relativistic beam models for the production of the high-energy emission. The decay of neutral pions created in the hot region produces photons with energies up to several hundred MeV. Relativistic pairs created as a result of charged pion decays produce additional inverse-Compton radiation in the range $\approx$ 1 keV–4 MeV if the pairs are exposed to UV radiation, or in the range $\approx$ 40 keV–150 MeV if the pairs are exposed to soft X-rays. This suggests that high-energy flares in AGNs may be triggered by changes in the disk structure (such as phase transitions or the development of electron scattering coronae) that temporarily shield the hot inner region from UV photons emitted at larger radii, thereby reducing the optical depth for MeV/GeV $\gamma$-rays. Stochastic processes may also play a role in accelerating the ultrarelativistic electrons responsible for producing the highest energy (GeV) emission.

*Subject headings:* accretion, accretion disks — black hole physics — galaxies: active — gamma rays: theory

## 1. INTRODUCTION

Before the launch of *CGRO,* AGNs were known to emit in the X-ray range (2–100 keV) and some also at a few MeV (Bassani & Dean 1983). Observations above 100 MeV had been made of only the nearest ($z$ = 0.158) quasar 3C 273 (Swanenburg et al. 1981). EGRET, the high-energy instrument of *CGRO,* has by now detected 22 radio-loud AGNs (Fichtel et al. 1993), among them OVVs, BL Lac objects, and objects with superluminal motion, with power-law spectra with an average photon spectral index of $\alpha \approx 2.0$. In some of these sources, the power emitted in the EGRET energy range dominates the entire multifrequency spectrum.

These observations have spawned a lot of theoretical research aimed at explaining this emission. Most of the models proposed so far include relativistic outflow from the center of the AGN, assumed to be a supermassive black hole. These models, however, suffer from Compton drag which decelerates the electrons and therefore degrades the MeV/GeV emission in the vicinity of the central source. To overcome this difficulty, we propose that hot ion disks with ion temperatures of up to $10^{12-13}$ K can produce the observed $\gamma$-ray luminosity. We outline the theoretical premises of our model, which extends the previous work of Eilek & Kafatos (1983, hereafter EK), and show multifrequency data of some of the AGNs detected by EGRET together with theoretical spectra from our model.

## 2. THE MODEL

Models for the high-energy emission based on plasma beams postulate the existence of ultrarelativistic particles that produce $\gamma$-rays by upscattering soft photons, without explaining how the required particle energies are maintained in spite of severe radiative losses experienced near the center of the nucleus. In the absence of a highly efficient reacceleration mechanism, radiative losses restrict the Lorentz factor well below $\gamma L \approx 10^4$, required by electron-scattering scenarios invoking IC or SSC emission in beams. Besides, there are a number of unresolved theoretical issues regarding the nature of the primary particle acceleration mechanism producing the highly collimated relativistic outflows. The observation that all of the EGRET AGNs show signs of collimated relativistic outflow such as apparent superluminal motion, flat radio spectra, rapid optical variability, and high polarization implies that accretion disks in these systems are being viewed close to face-on. This is true whether or not the high-energy emission arises in an associated jet. It is therefore interesting to consider emission from the disk itself as an alternative or supplement to relativistic beam models for the production of the observed high energy radiation. Because the $\gamma$-$\gamma$ optical depth increases with increasing propagation angle measured from the rotation axis, MeV and GeV radiation can only be observed from face-on disks. This provides a natural explanation for the preferential detection of AGNs with jets aligned close to the line of sight.

EK have shown that proton temperatures of $10^{12-13}$ K can be produced in two-temperature accretion disks around Kerr black holes, where the innermost radius is $1.2 r_g$. In the hot, two-temperature disk model, high-energy particles and $\gamma$-rays arise as a natural consequence of accretion onto rapidly spinning black holes. The decay of pions created in proton-proton collisions can produce primary $\gamma$-rays with energies up to a few hundred MeV, as well as significant quantities of relativistic $e^+e^-$ pairs with Lorentz factors $\gamma \leq 300$. These pairs can upscatter soft photons in their vicinity to form a second emission component at keV and MeV energies. This results in a large optical depth for MeV/GeV $\gamma$-rays, so normally, the source is optically thick at these energies. The observed outbursts in this model are due to shielding of the soft photons from the energetic particles, which causes a sudden reduction in the optical depth. This shielding may be triggered by disk instabilities, which are predicted for such hot accretion disks, allowing the MeV/GeV photons to escape from the source region. The typical timescale for variability is of the order of $\approx 1$ week for a viscosity parameter $\alpha = 0.1$ (Becker, Kafatos, & Maisack 1994). This is the order of magnitude observed for 3C 279 (Kniffen et al. 1993).

The model has been described in detail by Becker & Kafatos (1993), who also examined the effect of stochastic acceleration, which is not included in the theoretical curves shown here. Instead, we attempt to fit the observations using a simplified model that only includes the effects of synchrotron and inverse-Compton losses, and particle injection and escape. Here we apply the model to X-ray and gamma-ray data of some of the AGNs observed by EGRET (Fichtel et al. 1993). Other than that, data obtained from multifrequency databases are used. We point out that the latter data are not simultaneous with the EGRET observations. Since the sources are known to be variable in all energy bands, these data have been used only as a rough guide to the fits made to the multifrequency spectra.

Looking at the set of models shown in EK, we find that only the model with Comptonization parameter $y = 0.3$, viscosity parameter $\alpha = 0.1$, and accretion rate $\dot{M}/M = 10^{-8}$ yr$^{-1}$ can reproduce the observed emission in sources where the $\gamma$-ray power exceeds that emitted in X-rays. The remaining free parameters are black hole mass, soft photon frequency, and the number of relativistic electrons produced. We find that the black hole mass, which determines the magnitude of the X-ray and $>100$ MeV flux, ranges from several times $10^6$ to $10^{10}\, M_\odot$. A soft photon frequency of several keV is required to produce (by superposition with the pion decay component) the power-law spectra observed by EGRET. The electron production rate we obtain scales with the black hole mass. This basically reflects the fact that the spectral shape of the EGRET spectra of the various sources are very similar, namely power-law spectra with indices around $\alpha \approx 2$. An additional acceleration mechanism is required in order to achieve the highest observed photon energies. As discussed by Becker & Kafatos (1993) and by Becker et al. (1994), MHD wave turbulence driven by the hot protons may provide the necessary coupling between the ions and the relativistic electrons.

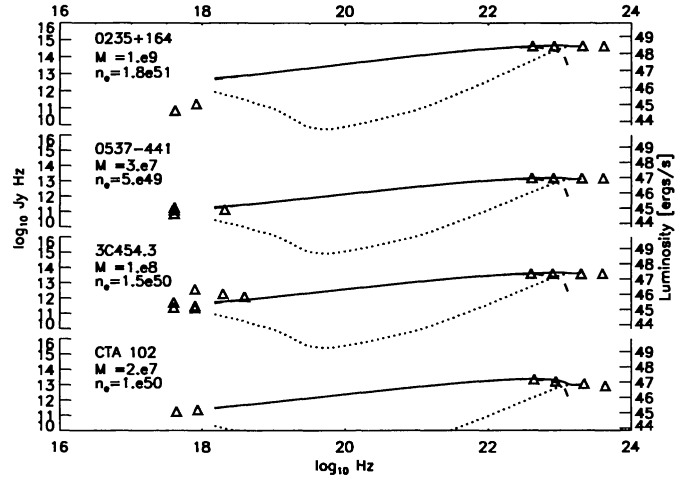


FIG. 1.—Hot disk model fits to the EGRET spectra of four AGNs, with earlier X-ray data as guides for the fits. Also given are the black hole mass and the number of relativistic electrons injected per second.

Figure 1 shows multifrequency data and the hot disk model spectra for four EGRET AGNs: 0235+164, 0537−441, 3C 454.3, and CTA 102. The dashed line shows the disk component; the dotted line, the emission from the relativistic pion-decay electrons. The solid line is the sum of the two components.

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