Unbeamed $\gamma$-rays from low luminosity AGNs

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Abstract. Proton-proton collisions in two-temperature accretion flows may lead to substantial $\gamma$-ray emission through neutral pion production and decay. We present preliminary results of our study of such a hadronic $\gamma$-ray emission. We find that radiatively inefficient flows around rapidly rotating black holes can produce the MeV/GeV luminosities up to $\sim 10^{44}$ erg s$^{-1}$. The hot-flow model predictions for the hadronic and the Comptonization components can put interesting constraints on the properties of the source of high-energy radiation in AGNs. As an example, we compare our model with X/$\gamma$-ray observations of Centaurus A and we find that the model with a maximally rotating black hole strongly overpredicts the $\gamma$-ray flux.

1. Introduction
Optically thin, two-temperature accretion flows with low radiative efficiency have been considered as the explanation of a variety of black hole systems and substantial work has been done to investigate their dynamical and spectral properties (see, e.g., a review in [1]). However, the work done so far focused on the radiation produced by electrons, while little attention has been paid to hadronic processes which could produce a considerable amount of high energy radiation since the proton temperature is very large in such flows. Already Shapiro, Lightman & Eardley realized, in their classical paper [2], that two-temperature flows can develop a significant $\gamma$-ray luminosity above 10 MeV, $L_\gamma$, through $\pi^0$ production; their rough estimate indicated a strong dependence of $L_\gamma$ on the spin of the black hole and, then, they suggested that this effect may serve as a means to measure the spin value. A few attempts of detailed prediction of the $\gamma$-ray flux from $\pi^0$ decay in hot flows followed this initial finding and only two such studies [3,4], embodying the recent progress in the hot accretion theory, have been done during the last fifteen years. As we note in Section 2, both models [3,4] are subject to certain shortcomings; their results have not been compared with $\gamma$-ray measurements from black holes, apart from the CGRO/EGRET detection from the direction of the Galactic Center.

A more careful investigation of the $\gamma$-ray emission from hot accretion flows appears to be a very timely effort, given the significant progress in our exploration of the $\gamma$-ray activity of AGNs thanks to the Fermi mission. Motivated by this, we extend our model of radiative processes in hot flows [5] by including the description of the hadronic $\gamma$-ray production. The basic features of our model and predictions for the $\gamma$-ray emission are presented in Section 2. The detections of radio galaxies by Fermi [6] establish a particularly interesting area for application of our results.
In Section 3 we briefly compare our model with FR I radio galaxies, focusing on the best studied object from this class, Centaurus A.

2. High-energy emission from hot accretion flows

We have recently developed a model of optically thin, two-temperature accretion flows involving an exact Monte Carlo treatment of global Comptonization as well as a fully general relativistic (GR) description of both the radiative and hydrodynamic processes, see [5]. In our model we consider a black hole, characterised by its mass, $M$, and angular momentum, $J$, surrounded by a geometrically thick accretion flow with an accretion rate $\dot{M}$. The inclination angle of the line of sight to the symmetry axis is given by $\theta_{\text{obs}}$. Below we use the dimensionless accretion rate, $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, and the spin parameter, $a = J/(cR_g M)$, where $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/c^2$, $L_{\text{Edd}} \equiv 4\pi GMm_p c/\sigma_T$ and $R_g = GM/c^2$.

In [5] we considered only the cooling of electrons and in our next work, in preparation, we extend the model to study the $\gamma$-ray production through proton-proton interactions. As pointed out in [7], Coulomb collisions are too inefficient to thermalize protons in optically thin flows; indeed, we find that in our solutions the accretion time-scale, $t_a$, is much shorter than the proton relaxation time-scale, $t_p$, e.g. $t_a \lesssim 1$ hour and $t_p > 1$ year for $M = 2 \times 10^9 M_\odot$ and $\dot{m} = 0.1$ within a few innermost $R_g$. Then, the protons are unable to redistribute their energy through Coulomb collisions and the proton distribution function is determined by the poorly understood viscous heating mechanism. This introduces a significant uncertainty in modeling the hadronic component, as the $\gamma$-ray flux and spectrum strongly depend on the distribution of proton energies, see [3]. We consider two cases:

(i) a Maxwellian distribution of protons, with temperature, $T_p(R)$, determined by the hydrodynamic solution; this case is most likely unrealistic (as $t_a \ll t_p$) but it allows to estimate the minimum level of $\gamma$-ray luminosity for a given set of model parameters,

(ii) a power-law distribution, $n_p(E) \propto E^{-s}$, with the radial-dependent power-law index, $s(R)$, determined by the requirement that the average energy of protons is the same as in case (i) at each radius $R$. Note that [3] and [4] considered a different non-thermal model, namely, the total dissipated power was assumed to heat only a small part of the proton population, leading to even more efficient $\gamma$-ray production than in our model.

For a given distribution of protons (thermal or non-thermal) we determine the $\gamma$-ray spectrum in the plasma rest frame, strictly following [8], and then we compute the transfer of $\gamma$-ray photons in curved space-time.

Figure 1 shows the radial distributions of parameters crucial for radiative processes and Figure 2 shows the broadband spectra produced in our models with $M = 2 \times 10^9 M_\odot$, $\dot{m} = 0.1$ and two extreme values of the spin parameter, $a = 0$ and $a = 0.998$. Furthermore, these models assume the viscosity parameter, $\alpha = 0.3$, and a rather weak magnetic field, with the magnetic pressure equal 1/10th of the total pressure. Note a strong difference between the dependence of the Comptonization and the hadronic components on the black-hole spin parameter.

Properties of the Comptonized radiation in our models are discussed in detail in [5], here we give a brief summary. We have studied in detail the hot flow solutions only for $\dot{m} = 0.1-0.5$, for which the luminosities of the flows are between $\sim 10^{-3}$ and $10^{-2} L_{\text{Edd}}$ and the X-ray spectra are rather hard, with the photon spectral index $\Gamma \sim 1.6$. These parameters, just below the turning point in the $\Gamma-L/L_{\text{Edd}}$ relation observed in both AGNs and black-hole binaries (see discussion and references in [5]), probably correspond to maximum luminosities of flows cooled by the Comptonization of synchrotron emission; we currently investigate solutions at lower $\dot{m}$. Rotation of the black hole stabilizes the circular motion of the flow which yields a higher density (through the continuity equation) within the innermost $\approx 10 R_g$, see Figure 1b. The resulting large difference between the Coulomb heating in models with a non-rotating and a rapidly rotating black hole is, however, outweighed by a strong contribution of the compressive heating.
Figure 1. The radial profiles of the electron and proton temperature (a); the proton number density (b); and the proton (black, red) and electron (blue, magenta) cooling rates (c), in hot flow models with $M = 2 \times 10^8 M_\odot$ and $\dot{m} = 0.1$. In all panels, the solid (black, blue) lines are for $a = 0.998$ and the dashed (red, magenta) lines are for $a = 0$. In panel (c), $Q$ denotes a vertically integrated rate, so $QR^2$ gives cooling rates (per unit volume) times volume.

Figure 2. (a) The angle-averaged spectra produced in optically thin, two-temperature flows; the synchrotron+Compton (radio–hard-X-rays) and the hadronic ($\gamma$-rays) components are shown separately. The solid lines are for $a = 0.998$ and the dashed lines are for $a = 0$. The blue line is for a power-law distribution of protons, the remaining $\gamma$-ray spectra are for a thermal distribution. (b) Angular distribution of the $\gamma$-ray spectrum for $a = 0.998$ and the power-law distribution of protons; $\theta_{\text{obs}} = 15, 40$ and $80^\circ$ from bottom to top.

of electrons, much less dependent on spin. The flows have radiative efficiencies of $\eta \simeq 0.004–0.01$ in the considered range of luminosities.

In turn, the hadronic radiation is much more sensitive to the spin parameter. The stabilized rotation of the flow results in a much stronger dissipative heating in the inner region for $a = 0.998$, yielding a much larger proton temperature, see Figure 1a. As a result, the $\gamma$-ray luminosity is comparable to the X-ray luminosity for $a = 0.998$, while for $a = 0$ it is weaker by over 3 orders of magnitude, see Figure 2a. For the power-law distribution of protons, the energy index approaches $s \simeq 2.1$ in the innermost region in the model with $a = 0.998$ and the resulting $\gamma$-ray spectrum extends to much higher energies than the spectrum produced in the thermal proton model.

Our model of hadronic emission involves crucial improvements with respect to the previous studies. The self-similar solution of the flow structure, underlying the calculation of the $\gamma$-ray spectrum in [3], gives a very inaccurate approximation of the innermost region even for flows around a non-rotating black hole, whereas detailed predictions of the hadronic emission are very sensitive to the details of the flow structure in that region. [4] refined the model by using a GR model of the flow, however, they neglected the Doppler and gravitational shifts of energy as well as gravitational focusing and capturing by the black hole. As we can see in Figure 1c, the emissivity of the $\gamma$-rays is strongly concentrated within the innermost few $R_g$, then, neglecting the effects of gravitational redshift and the capturing of photons results in a significant overestimation of $L_\gamma$ detected far away from the flow.
Figure 2b illustrates another GR effect, related to the properties of the Kerr metric. Trajectories of photons emitted close to a rapidly rotating black hole are strongly bent toward the equatorial plane and the produced radiation may have a significant intrinsic anisotropy (see e.g. [9]). The magnitude of this anisotropy depends on the radial emissivity of a spectral component. For the Comptonized radiation the emissivity profile is rather flat and the anisotropy is reduced due to mixing of radiation produced in the innermost part with that from more distant regions. For the hadronic component the dependence on $\eta_{\text{obs}}$ is very pronounced, with the difference by two orders of magnitude between the fluxes detected by face-on and edge-on observers, and a significant difference between the spectral shapes.

We have not included the effect of $\gamma\gamma$ absorption in our computations yet, which is currently the major shortcoming of our model. Very rough estimations, with an isotropic approximation of the photon field, indicate that for $\dot{m} = 0.1$ the flow is transparent for photons with energies $\lesssim 1$ GeV but the innermost part is opaque for photons with higher energies. Exact calculations, taking into account the angular distribution of photons in the flow, are required for accurate assessment of this effect. We can expect that the probability of absorption strongly depends on the direction of photon escape. The density of the photon field increases with increasing $\dot{m}$ and we expect that the $\gamma$-rays cannot escape from the central region for $\dot{m} > 0.1$. Then, the models shown in Figures 1 and 2 correspond roughly to the largest $L_{\gamma}$ (of $\sim 10^{44}$ erg s$^{-1}$ for large values of $M$, $a$ and $\theta_{\text{obs}}$) which can be expected from accretion flows in the specific accretion scenario considered in our model.

Finally, we note that proton-photon interactions are much less efficient than proton-proton interactions in the central region of the flow. Namely, the number density of $\gamma$-ray photons, which can effectively interact with protons in photomeson production, is by a factor of $\sim 10^3$ smaller than the number density of protons, $n_p$, within the innermost few $R_g$: the number density of hard X-ray photons, which can interact with protons in photopair production, is similar to $n_p$. The cross-section for both channels of proton-photon interactions is by over two orders of magnitude smaller than the cross-section for proton-proton interaction, making the photo-hadronic production of secondary particles negligible.

3. Comparison with observations
It was suggested already by [10] that tenuous, two-temperature flows may be responsible for the low nuclear luminosities in radio galaxies with large radio lobes. Currently, a substantial observational evidence indicates that accretion flow typically proceeds through the radiatively-inefficient mode below a characteristic luminosity of $\approx 0.01 L_{\text{Edd}}$ in AGNs (e.g., [11]). FR I radio galaxies make a class of objects observed at such luminosities which are particularly interesting for our study, as the key property required for large $L_\gamma$ in our model - i.e. rapid black-hole rotation - can be expected primarily in jet sources. Remarkably, an average radiative efficiency, $\eta \lesssim 0.005$, estimated for FR Is by [12] is consistent with the values of $\eta$ obtained in our hot flow solutions. Furthermore, our model, in which the synchrotron emission is the main source of seed photons, predicts a hardening of the X-ray spectrum with increasing luminosity, which is indeed observed in low-luminosity AGNs; interestingly, the values of $\Gamma$ and the $2-10$ keV luminosity, $L_{2-10}$, measured in two well known, $\gamma$-ray emitting FR I galaxies, Cen A (e.g. [13]) and M87 [14], agree with the $\Gamma \sim L_{2-10}/L_{\text{Edd}}$ relation determined for low luminosity AGNs, e.g., in [15]. [16] investigate the X-ray emission, using the coupled jet/accretion-flow model, in a sample of FR I radio galaxies and they conclude that the jet emission may dominate only in the least luminous sources, with $L_{2-10} \lesssim 5 \times 10^{-6} L_{\text{Edd}}$.

The MeV/GeV luminosities measured in FR Is are between $\approx 10^{41}$ and $10^{44}$ erg s$^{-1}$ [6], and, as we note above, such $L_\gamma$ can be produced by hot flows with $\dot{m} \lesssim 0.1$ around rotating black holes. The steep slopes of the $\gamma$-ray spectra determined in most FR Is, with $\Gamma_\gamma \gtrsim 2.2$, are consistent with the softness of spectra from $\pi^0$ decay; a simple power-law gives a good representation of the
observed data, but their quality does not allow to rule out spectral curvature which characterizes the $\pi^0$ decay spectra. NGC 1275, with a flat $\gamma$-ray spectrum, cannot be explained by our hadronic model; this source may contain a significant contribution from the jet, as suggested also by its location in the region occupied by BL Lacs in the $\Gamma\gamma-L_\gamma$ plane (see fig. 6 in [6]) as well as by the very small inclination of the jet axis to the line of sight, of $<3^\circ$ close to the core [17].

![Figure 3.
](image)

**Figure 3.** Nonsimultaneous observational data of Cen A by INTEGRAL and Fermi, see [18], compared with our model spectra. The solid-black and dashed-blue lines show the Comptonization spectra for $a = 0.998$ and $a = 0$, respectively. The solid-red line shows the hadronic spectrum, rescaled by a factor of 0.05, for $a = 0.998$ in the model assuming a power-law distribution of protons. The dashed-magenta line shows the thermal hadronic component for $a = 0$. The spectra for $a = 0.998$ correspond to $\theta_{\text{obs}} = 50^\circ$. The green squares, red squares and blue circles show the INTEGRAL/JEM-X, INTEGRAL/SPI and Fermi data, respectively. The observed spectrum is strongly absorbed below 10 keV, which effect is not taken into account in the model spectra. Normalization of the model spectra corresponds to the distance of 3.8 Mpc.

Thanks to its proximity, Centaurus A is the best studied FR I radio galaxy, suitable for detailed testing of various accretion models through modeling of its broadband spectrum. Its X-ray luminosity, $L_{2-10}/L_{\text{Edd}} \simeq 10^{-4}$, satisfies the criterion, suggested in [16], for a FR I galaxy to be dominated by a hot flow rather than a jet emission. In Figure 3 we compare the Comptonization and hadronic spectra from our model with the X/$\gamma$-ray observations of Cen A, described in [18].

As we discuss in [5], our model approximately reproduces the luminosity and the slope of the X-ray emission in Cen A; furthermore, it predicts very small changes of $\Gamma$ corresponding to the change of $L_{2-10}$ by a factor of 3 (as typically observed in Cen A) which appears to be compatible with the reported spectral variability within $\Gamma \simeq 1.7$–1.8 only. On the other hand, the spectral break energy of $\sim 200$ keV, reported in [18], is inconsistent with breaks at $\sim 500$ keV predicted in our models. Furthermore, the $a = 0.998$ model predicts a slightly harder spectrum than that observed, as can be seen in Figure 3. However, an additional process, which would lead to a softening of the spectrum and a decrease of the cut-off energy, has to be included in the model for large values of $a$. Namely, an efficient non-thermal synchrotron emission from relativistic $e^\pm$, coming from the decay of charged pions copiously produced, together with $\pi^0$, through proton-proton collisions, would provide a strong seed photon input in addition to the thermal synchrotron emission. We have performed initial calculations confirming that this effect should be crucial in approaching the agreement between the model with a rotating black hole and the hard X-ray data.

As illustrated in Figure 3, the prediction for the $\gamma$-ray flux may be strongly constraining for the black hole spin if $\dot{m}$ is determined by the X-ray flux. For Cen A, the detected MeV/GeV flux cannot be explained by emission from the flow around a slowly rotating black hole. For a maximally rotating black hole, the predicted $\gamma$-ray flux exceeds the measurement by a factor of $\sim 10$ (the exact value depends on $\theta_{\text{obs}}$) and we conclude that the black hole in Cen A cannot...
rotate at the maximum velocity, if the X-ray emission is produced by thermal Comptonization in an optically thin flow.

The (rescaled) hadronic spectrum for the power-law distribution of protons is in agreement with the Fermi data points except for the lowest energy bin. An excess at these energies could be possibly explained for the plasma containing two populations of protons: a subrelativistic thermal-like population, giving a contribution similar to that shown by the dashed curve for $a = 0$, and a non-thermal one.

4. Discussion
FR I radio galaxies are supposed to be the parent population of BL Lacs and their radiation is often interpreted as jet emission observed at large inclination angle to the jet axis and thus subject to less efficient Doppler boosting. Spectral energy distributions of FR Is are indeed consistent with a jet model, however, the Lorentz and Doppler factors required by such models are much lower than typical values found in models of BL Lac objects, see [6]. Therefore, the radiation observed in FR Is and BL Lacs must have a different origin; otherwise the debeamed radiation seen in the latter would be much weaker than that observed in FR Is. This has led to the development of complex models explaining a significant spread of the bulk velocity of the emitting plasma in the jet. However, this deprives the jet model of its major attracting feature, i.e. the simplicity by explaining differences between FR I and BL Lac objects through orientation effects only.

Addressing the problem of the origin of the high-energy radiation from FR Is, we note that $\gamma$-ray detections, usually regarded as the evidence that the observed radiation originates from the jet, can be alternatively explained by the hadronic emission from a hot flow. Our preliminary comparison of the X/$\gamma$-ray spectrum observed from Cen A with the hot flow model spectra suggests that this object can be explained by the model with a submaximally rotating black hole. A more detailed comparison will be done in our future work, in which we will take into account additional effects from hadronic processes in the X-ray spectra as well as the absorption of $\gamma$-rays.

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