Radiation from hot accretion flows onto black holes

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Resumen / Los flujos de acreción calientes que tienen lugar alrededor de agujeros negros consisten en plasmas ópticamente delgados, en donde los electrones pueden alcanzar temperaturas de hasta 10^{10} K y producir radiación por sincrotrón, bremsstrahlung y Compton inverso, y los iones pueden alcanzar temperaturas de hasta 10^{12} K y producir emisión gamma a través de interacciones protón-protón. En este trabajo, consideramos un modelo particular de un flujo de acreción caliente y estimamos las distribuciones espectrales de energía que resultan de la emisión de ambas especies de partículas.

Abstract / The hot accretion flows upon black holes are usually optically thin two-temperature plasmas in which electrons can achieve temperatures up to 10^{10} K, producing radiation via synchrotron, bremsstrahlung and inverse Compton, and the ions can reach temperatures up to 10^{12} K. The hottest ions might produce gamma emission through proton-proton interactions. In this work, we considered a particular model of a hot accretion flow and estimate the spectral energy distributions produced by both species of particles.

Keywords / stars: black holes — accretion, accretion disks — radiation mechanisms: thermal

1. Introduction

Black hole accretion is a fundamental physical process in the universe and it is the primary power source behind Active Galactic Nuclei (AGNs), Black Hole Binaries (BHBs) and possibly Gamma Ray Bursts (GRBs). This process occurs via an accretion disk, or more generally an accretion flow, where fluid particles slowly lose energy and angular momentum and move inwards to the black hole. Accretion flows can be classified into two broad classes: cold and hot. Cold accretion flows, with temperatures in the range $10^4 - 10^7$ K, are radiatively efficient, optically thick flows, and hence they typically emit as a multi-temperature blackbody (Shakura & Sunyaev, 1973; Page & Thorne, 1974). Cold disk models are capable to explain the spectrum of quasars and BHBs in the high-soft state but they fail under other circumstances; for example they cannot explain the spectrum of BHBs in the low-hard state. This gave rise to a family of different accretion models characterized by the presence of a much hotter plasma (Bisnovatyi-Kogan & Blinnikov, 1977). These hot accretion flows are optically thin and the energy exchange between ions and electrons is inefficient yielding that these particle species have different equilibrium temperatures. In the central regions of these flows temperatures might be as high as 10^{9-10} K for electrons, and up to 10^{12} K for ions (Narayan & Yi, 1995). One of the most useful models of hot accretion flows are those of the family of Advection Dominated Accretion Flows (ADAFs) that, being radiatively inefficient, are dominated by advection onto the black hole (Narayan & Yi, 1994, 1995). In these flows the radiation that is locally produced by synchrotron and free-free (thermal bremsstrahlung) emission escape with none or little interaction. However, in some scenarios comptonization of photons by the hottest electrons can significantly modify the spectrum. In this article we investigate the thermal emission produced by electrons and ions in a particular analytical model of a hot accretion flow.

The article is organized as follows: in Sec. 2. we present the main characteristics of the accretion model and we briefly discuss the relevant processes taken into account that produce thermal emission. In Sec. 3. we show some spectral energy distributions for different set of parameters.

2. Accretion flow model

We consider the accretion model applied to Sgr. A* by Straub et al. (2012), which is based on the formalism developed by Abramowicz et al. (1978). The flow consists in a perfect fluid torus orbiting a Kerr black hole. The equation for conservation of energy and momentum can be easily solved yielding an expression for the gravitational potential function:

$$W(r,\theta) = \frac{1}{2}\ln\left[-\frac{g_{tt} + 2\Omega g_{t\phi} + g_{\phi\phi}}{(g_{tt} + \Omega g_{t\phi})^2}\right]. \quad (1)$$

Here, Ω is the angular velocity of the torus and $g_{\alpha\beta}$ are the metric components. The equipotential surface that defines the torus boundaries crosses itself in a cusp through which accretion onto the black hole may occur without the need of viscosity and the subsequent loss of angular momentum (it is a Roche lobe overflow). Assuming a two-temperature gas and a polytropic equation of state we can obtain analytical expressions for the temperatures of both species:

$$T_{\rm e} = \Big[(1-\omega)\mathcal{M} + \omega\mathcal{M}_\xi\Big]\mu_{\rm e}\frac{(1-\beta)m_{\rm u}P}{k_{\rm B}\epsilon}, \quad (2)$$

Table 1: Parameter values in Fig. 1.

Parameter	Value
M	4×10^{8} $\mathrm{M}_\odot$
a	$0.9M$
λ	0.7
$T_{\rm e,c}$	10^{10} K
ξ	10^{-2}
$\epsilon_{\rm c}$	10^{-16} g cm^{-3}
β	0.5
n	3/2

$$T_{\rm i}=\left[\frac{\mu_{\rm e}}{\mu_{\rm i}}\mathcal{M}+\omega(\mathcal{M}-\mathcal{M}_\xi)\right]\mu_{\rm i}\frac{(1-\beta)m_{\rm u}P}{k_{\rm B}\epsilon}, \qquad (3)$$

where ω is a dimensionless potential, β is the magnetic pressure to total pressure fraction, $\beta=P_{\rm mag}/P$, ϵ is the mass density, $\mu_{e,i}$ are the mean molecular weights for each species, $m_{\rm u}$ is the atomic mass unit, $k_{\rm B}$ is the Boltzmann constant, $\mathcal{M}=\mu_{\rm i}/(\mu_{\rm e}+\mu_{\rm i})$, and $\mathcal{M}_\xi=\mu_{\rm i}\xi/(\mu_{\rm e}+\mu_{\rm i}\xi)$.

In order to calculate the thermal spectrum of the torus, we divided it in cells distributed equispacedly in radii and polar angles (there is axial symmetry). We considered that electrons produce radiation via free-free emission by the interaction with both electrons and ions and, as the flow might be considerably magnetized, the hottest emit synchrotron radiation. We also take into account synchrotron self-absorption at low frequencies. The photons produced by these two local processes can be Compton-scattered to higher energies by the most energetic electrons. This process is non-local and to treat it we adopt the scheme developed by Narayan et al. (1997) for ADAFs, in which multiple comptonization is included and radiative transfer is solved iteratively. In addition, we take into account the gravitational redshift of the radiation.

On the other hand, ions can achieve temperatures up to 10^{12} K and hence those on the tail of the Maxwellian distribution have energies high enough to produce neutral pions through proton-proton interactions. These neutral pions decay with a lifetime of 10^{-16} s almost always into two gamma rays; therefore we consider this emission process.

3. Spectral energy distributions

The analytical model considered depends on a set of free parameters, namely the dimensionless specific angular momentum of the torus λ, the central electron temperature $T_{\rm e,c}$, the electron to ion temperature ratio at the torus center ξ, the central mass density $\epsilon_{\rm c}$, the magnetic pressure to total pressure fraction $\beta=P_{\rm mag}/P$, the polytropic index n, and the mass and specific spin of the black hole, M and a, respectively.

Fig. 1 shows the spectrum for the particular set of parameter values showed in Table 1. It can be seen that synchrotron emission is self-absorbed at low frequencies and there the spectrum follows the Rayleigh-Jeans law. The blue line is the inverse Compton spectrum, which

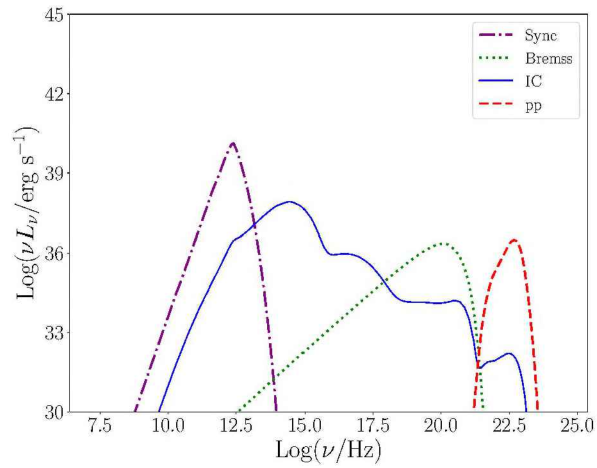

Figure 1: Thermal spectrum for $M=4\times10^{8}$ $\mathrm{M}_\odot$, $a=0.9M$, $\lambda=0.7$, $\epsilon_{\rm c}=10^{-16}$ g cm^{-3}, $T_{\rm e,c}=10^{10}$ K, $\xi=0.2$

presents several well-defined peaks corresponding to the multiple scattering that a photon can suffer before leaving the torus. In this scenario ions at the center of the torus have a temperature of 10^{12} K and produce MeV photons.

Fig. 2 shows different spectra obtained by changing one parameter and keeping fixed the others to the values in Table 1. In the upper-left panel the central electron temperature is changed implying significant variations on the spectrum. In particular, comptonization tends to harden the spectrum as the temperature increases. Additionally, as the electron to ion temperature is keeping fixed, ions also have different temperatures and the pp emission is significantly modified. In the upper-right panel the torus specific angular momentum is changed. Though the effect is not very significant, the higher the value of λ, the larger the torus extension and hence the luminosity. In the lower-left panel the central mass density is changed. As it is expected, higher densities produce an enhancement of the whole spectrum but specially of the inverse Compton one. Finally, in the lower-right panel the magnetic pressure to total pressure fraction is changed and only the synchrotron spectrum and its correspondent Compton-scattered spectrum are modified.

This preliminary work will be extended by including non-thermal population of particles in order to have a robust model that can be applied to different kind of sources such as Seyfert galaxies or BHBs.

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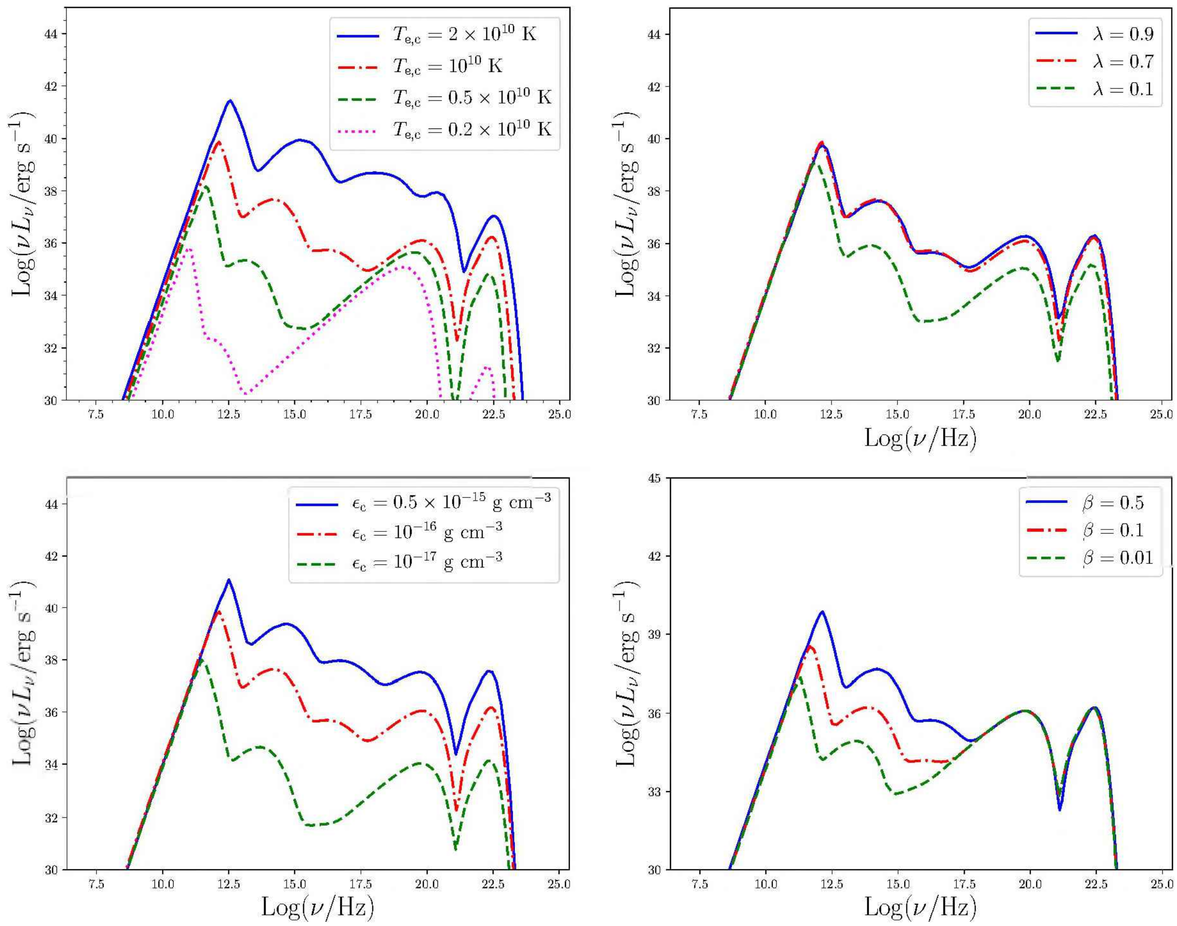

Figure 2: Different plots of the torus spectrum. The parameters are the same as in Figure 1 except those explicitly mentioned. *Upper-left panel:* the central electron temperature is changed. *Upper-right panel:* the dimensionless specific angular momentum parameter is changed. *Lower-left panel:* the central mass density is changed. *Lower-right panel:* the magnetic field pressure to total pressure fraction is changed.

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