The spectral energy distribution of an X-ray pair halo from a gamma-ray source with a power-law continuum

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Abstract. Interactions between Very High Energy (VHE) gamma-rays from Active Galactic Nuclei (AGNs) and infrared photons from the Extragalactic Background Light (EBL) can start electromagnetic cascades. If the extragalactic magnetic field near a host galaxy is strong enough ($\sim$1 μG), the cascades would develop isotropically around the AGN. As a result, the electron/positron pairs created along the development of the cascades would create an X-ray halo via synchrotron radiation process. It is believed that the VHE gamma-ray spectra from the AGNs could be approximated by a power-law model which is truncated at high energy end (i.e. maximum energy). In this work we studied the X-ray Spectral Energy Distribution (SED) of the halo generated from the AGN spectra with different power indices and maximum energy levels. The results showed that the SEDs were slightly higher and broader, as they were obtaining higher flux if the power indices were lower. On the other hand, the SEDs were sensitive to the maximum energy levels between 100-300 TeV. More flux could be obtained from the higher maximum energy. However, we found that the SED becomes insensitive to the varied parameters when the maximum energy and the power index are $>$ 500 TeV and $<$ 1.5, respectively.

1. Introduction

Very High Energy (VHE) gamma-rays from extra-galactic sources such as Active Galactic Nuclei (AGNs) have been considered as an origin of an electron-positron pair halo [1–3]. The detailed explanation of the model were published many years ago [4, 5]. The pair halo model is shown in figure 1. The VHE gamma-rays that propagate in the cosmological scale can be absorbed by the Extra Galactic Background (EBL) photons via the $\gamma\gamma$ pair-production interaction. The interaction, in turn, creates electron/positron pairs. These electron/positron pairs can interact with the Cosmic Microwave Background (CMB) photons and up-scatter them to be gamma-ray photons via inverse Compton scattering. These cyclic interactions are called electromagnetic cascades. Moreover, these electromagnetic cascades can develop isotropically around the an AGN if the extragalactic magnetic field around the galaxy is strong enough (1 nG - 1 μG). In fact, the electron/positron pairs from the cascades can also emit X-ray photons via synchrotron radiation process [6].

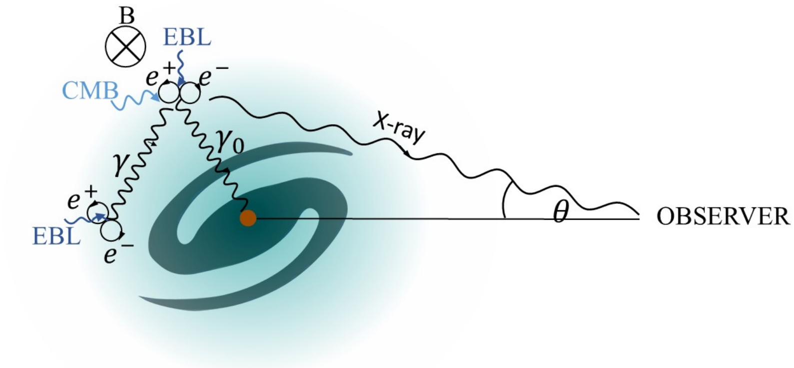

Figure 1. The diagram shows X-ray emission from a pair halo.

Observational data of the VHE gamma-ray data from AGNs can be simply described in the form of the power-law spectra. Some of them showed the absorption features [7] due to the EBL. These indicate the possibility of the existing of the electromagnetic cascades as well as the pair halos around the AGNs. The searches for the pair halo emission in the gamma-ray regime have been attempted during the last decades [8,9]. However, there has been no strong evidence of the halo emission confirmed yet. There have also been the alternative searches for the halo emission in the X-ray waveband. From these attempts, the results have begun to emerge [10, 11]. In our previous works [5,6], we studied the X-ray emission of the halo assuming that the intrinsic VHE gamma-rays from an AGN were in the form of mono-energetic gamma-ray spectra. These were for the sake of systematic studies. therefore, in this work, we used more realistic approaches. The X-ray pair halos from more realistic spectra were simulated and studied. the effects of the changes of power-index and maximum energy of the spectra on the SEDs of the X-ray pair halos were observed.

2. Methodology

The electromagnetic cascades were generated by intrinsic VHE gamma-rays from AGN, while the electron/positron pairs radiate synchrotron radiation during their gyrations. The synchrotron emission time distributions were computed during the simulations and used for calculating the spectral energy distribution (SED) of the halo.

In this work, it was assumed that an AGN had the gamma-ray luminosity of 10^{45} erg/s and located at $z \approx 0.1$ with an ambient magnetic field of 1 μG for all simulations. The intrinsic gamma-ray from the AGN was generated with power law spectra with power index, p, defined by the well known relation:

$$\frac{dN}{dE} \propto E^{-p}. \tag{1}$$

In the simulation, the gamma-ray photons have the energy between E_{min} and E_{max}. The E_{min} was fixed at 1 TeV, while the E_{max} and p were varied parameters. The energy of the gamma-ray with this spectrum was generated by transforming a random number, ξ, between 0 and 1 using the relation that we formulated,

$$E = \left(\xi(E_{max}^{-p+1} - E_{min}^{-p+1}) + E_{min}^{-p+1}\right)^{\frac{1}{-p+1}}. \tag{2}$$

The gamma-ray with this energy level was used as an input in the simulation as described in our previous works [5,6] to compute the SEDs of the X-ray photons from electron/positron pair halos. The effects of the power law spectra of the gamma-ray from the AGN on the X-ray SED from the pair halo were observed by varying the power index, p, and the maximum energy, E_{max}.

3. Results and discussion

In this work, we aimed to study responses of the SED and the flux of the X-ray pair halo to the power-law parameters – i.e the index p and maximum photons energy E_{max} – of the gamma-rays from the AGN. The parameters of the power-law spectra were varied as summarized in table 1. Thus, the changes of the X-ray SEDs were observed.

Table 1. The total synchrotron energy flux of X-ray pair halos with different power indices and maximum energy levels.

E_{max}	Energy flux (eV/cm^2 s)		
	$p = 1.5$	$p = 2.0$	$p = 2.5$
30 TeV	1.01	0.96	0.92
100 TeV	3.30	2.56	2.03
300 TeV	7.69	5.66	3.60
500 TeV	8.31	6.17	3.80

The results showed that the parameters did not affect the SEDs at the energy levels below 3 eV as shown in figure 2. However, at the energy above that level, the X-ray SEDs showed the responses to both parameters. The figure 2(a) shows how the SEDs changed in responses to three different values of the parameter E_{max} of the power-law. There are more fluxes in the higher energy bands when the E_{max} increased. However, it was found that the SEDs would reach the maximum level if the E_{max} reached ~300 TeV; from ~300 - 500 TeV, the SED as well as the total flux seems to be constant (or have only a small variability). This implies that, beyond the threshold level of E_{max} of 300 TeV, the X-ray pair halos would not depend on the parameter E_{max} of the power-law spectra.

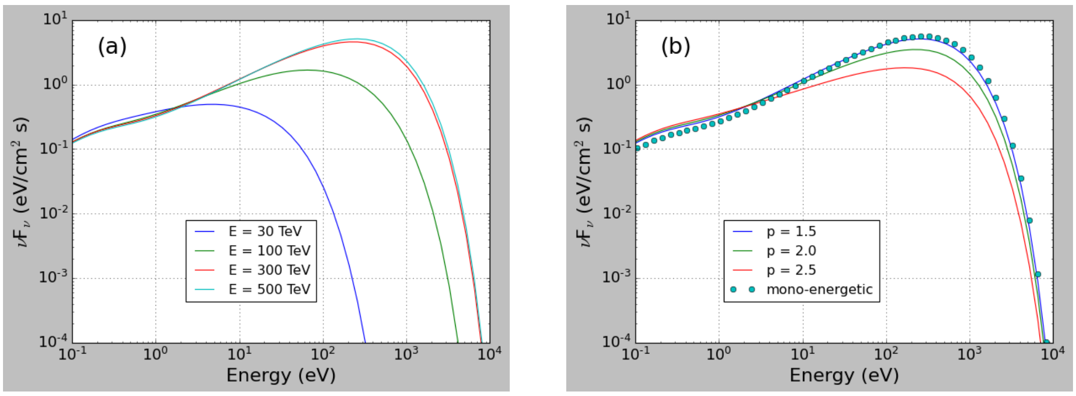

Figure 2. The SEDs of X-ray pair halo. (a) The comparison of the SEDs from different E_{max} levels at p =1.5. (b) The comparison of the X-ray SEDs from different power indices and a mono-energetic spectrum at E_{max} = 500 TeV.

On the other hand, the results also showed the effects of the power indices on the pair-halo X-ray fluxes (figure 2(b) and table 1) in which the lower power indices could yield the higher SEDs as well as the flux. We might explain this in the scenario that for the smaller power indices, there were more numbers of gamma-rays in higher energy bands that were responsible for triggering the electromagnetic cascades and, in turn, creating the electron/positron pair halos.

Similar to the case of varying the maximum energy, as the parameter p reach the value of 1.5 – i.e. the threshold value – it seems that the SEDs and the flux do not change significantly. Moreover, for comparison, in figure 2(b), we also over-plotted the SED obtained from mono-energetic spectrum of photon energy 500 TeV (see [6] for the detail calculation); we quote this SED as the halo SED that provide the maximum flux since all VHE photons have maximum energy (500 TeV). It could be seen that the SEDs from the values of $p = 1.5$ and $E_{max} = 500$ TeV, and that of the mono-energetic spectrum are well constitent. This implies that the X-ray pair halo SEDs would not depend on the power indices and maximum energy if their values exceed the their threshold values of 1.5 and 500 TeV, respectively, i.e. the similar SEDs and fluxes would be obtained.

Although the calculation of the observational feasibility of the halo is out of scope of this work, it could be worth to shortly mention this. The plots in figure 2 obviously show that, as the varied parameters change, the flux could vary mainly in the energy band of 10 – 5000 eV. Indeed, this covers in the observational band of current X-ray observatories such as *XMM-Newton* and *Chandra*. Nevertheless, since the halo flux is, actually, substantially low, comparing to the central AGN flux, in practise, it is difficult to distinguish the halo flux from the AGN flux (see e.g. [11]); one must be careful during the analysis to avoid the misleading result. However, given the high effective area and the good spatial resolution of the current and near future X-ray telescopes, the detection of the halo has been challenged.

4. Conclusion

In this work, we studied the SEDs in the X-ray waveband of the pair halo generated from the AGN which emits the VHE gamma-ray in the form of power-law continuum. Two varied parameters – power index and maximum photon energy – has been investigated how they affect the flux and shape of pair halo SEDs. It was found that these parameters could affect the SEDs of the X-ray pair halo, in which the halo flux could increase if the power index decreases and/or the maximum photon energy increases. However, if the values of the power index and the photon maximum energy exceeded their limits – i.e. $p < 1.5$ and $E_{\rm max} > 500$ TeV – the SEDs of the X-ray pair halos would seem to be source independent.

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