Searching for the electron/positron pair halo of the Blazar H1426+428 using XMM-Newton

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Abstract. Electron/positron pair halo is a physical phenomenon in which the very high energy gamma rays emitted from Blazar interact with cosmic infrared background (CIB) so that produce the electron/positron pairs; the produced electron/positron pairs could up-scatter the cosmic microwave background (CMB) reproducing the gamma-rays, thus these form the cascade process of producing the electron/positron pairs appearing as an halo around the blazar. In case that the halo presents in the ambient strong magnetic field, the electron/positron pairs could emit X-ray light via synchrotron process providing another opportunity to detect the halo. In this work, we search for the X-ray emission from the halo of the Blazar H1426+428 using the observed X-ray data from XMM-Newton observatory. The X-ray spectra of the halo are carefully extracted from the annulus, source free regions around the Blazar to avoid the X-ray contaminations from the Blazar itself and the nearby point sources. These spectra were fitted using the physical model which takes into account the emissions from the unresolved cosmic X-ray and instrument backgrounds. The unresolved flux of ≈ 10⁻¹³ erg s⁻¹ cm⁻² have been detected in the regions, and we argue that, at least, some fraction of the flux might be the emission from the halo.

1. Introduction
Active Galactic Nuclei (AGN) have been known as extragalactic sources of very high energy (VHE, E≫100 GeV) gamma-rays. During traveling in the cosmological scale, some of these gamma-rays cannot reach to us because they interact with infrared photons in Extragalactic Background Light (EBL) via γγ-pair production (PP). The absorption of the gamma-rays has been reported [1] and expected as an indirect tool for probing the EBL. The products of the absorption are pairs of energetic electron/positron that, in turn, can interact with microwave photons in Cosmic Microwave Background (CMB) to be VHE gamma-rays via inverse Compton scattering (IC). These second gamma-rays will redo the same processes as their ancestor did until their energies are not enough to be absorbed by the EBL photons. These processes are called the electromagnetic cascades. The study of the cascades neglect the effect of extragalactic magnetic fields (EGMFs) until the model of electron/positron pair halos was proposed in 1994 [2]. In the model, the EGMFs gyrate the electron/positron pairs in the cascades several rounds before proceed the cascades. As a result, the cascades develop isotropically around the AGN and create electron/positron pairs that can emit observable photons. Gamma-ray from inverse Compton scattering is the first type of the observable photons that people used for searching the pair halos.
The spectral energy distribution (SED) and the spatial distribution of gamma-ray predicted in 2009 [3] were used to find the signal of the pair halo. Searching pair halos with gamma-ray is very challenging because there are still no strong evidence from observation gamma-rays [4–5]. On the other hand, X-ray photons from synchrotron radiation of the electron/positron pairs could provide another promising window of opportunity for searching pair halos. It has been shown by [6] that the simulated SEDs of X-ray pair halos and the sensitivity of the XMM-Newton are comparable, suggesting the possibility of detecting a pair halo signal.

Blazar H1426+428 is one of the best candidates for searching a pair halo at least in the gamma ray regime. The redshift $z = 0.129$ of this object is the suitable distance for forming a pair halo. Moreover, this blazar has been reported the EBL absorption features in its SED [7–8], which means the electromagnetic cascades have already triggered. In this work, we will analysis the stacked X-ray data to search for the extended components of H1426+428, which could be the radiation from the pair halo.

2. Observations and data reduction

We searched for the X-ray data of the blazar H1428+428 from XMM-Newton science archive [9]. Out of eight observations found, we skipped one that is off-axis observation, and proceeded to study with only on-axis observations tabulated in table 1. Since the halo is theoretically predicted to radiate as a sphere around the central blazar (i.e. the halo) up to scale of Mpc [10], we skipped analysing the data obtained from the central CCD (see figure 1) to avoid the contamination from the central blazar, and focused on the data obtained from the other CCDs as shown in figure 1. We performed the data reduction and data analysis following the method suggested for analysing XMM-Newton observations of extended sources (XMM-ESAS cookbook) using XMM-ESAS package [11]. In brief, the observational data were reprocessed using the latest instrument calibration. Then, the observing periods which were highly affected by soft proton background flaring were removed to get the clean observational data. We also removed the data from CCDs which were in anomalous state (see column 4-5 of table 1 and figure 1). Finally, any point sources detected in the telescope’s filed of view were removed to minimise the contamination. The observational data created by these steps were then used to extract the energy spectra. In fact, we divided the observational data into three regions – region A, B and C – defined in figure 1 and extract the spectra from these individual regions, instead of extracting single spectrum from the entire region. This is to avoid creating the spectrum from the single area which varies in response matrix largely from inner edge to outer edge. Indeed, since each individual observation always had two data sets obtained from the MOS1 and MOS2 cameras, so we got six spectra in total from each observation. Finally, to gain S/N of the spectra for further analysis, we grouped the spectra of every observation obtained from the same region and camera together, and combined the spectra within each group using the package ADDSPEC [12]; however, since we lost the MOS1 and/or MOS2 data of some observations due to the anomalous state, so the spectra from each group were also divided into two sub-groups: i.e. ones affected and not affected by anomalous state. Using these criteria, we end up with 12 spectra. Each spectrum was grouped to have a minimum of 25 counts per bin to utilise the $\chi^2$ minimisation method during the spectral fitting and were then used as the basis for further analysis.

3. Spectral analysis and discussion

Here, we used an X-Ray Spectral Fitting Package (XSPEC) [13] to model the obtained X-ray spectra over the energy range of 0.5 - 5.0 keV. Since we had already removed all well know sources of X-ray emission, i.e. the central blazar H1426+428 and any significant point sources,
Figure 1. (a): the example MOS observation of the H1428+428. The overlaying green lines indicate the region A, B and C used in the analysis; the angular distance of each line from the centre is indicated by the white arrow. The blue dashed lines indicate the boundary of each CCD. (b): The model data (red) best fitted with the observed spectra (black) obtained from region A of MOS1 camera.

Table 1. XMM-Newton observational data of H1426+428.

| Observation ID      | Observing date   | Exposure time (ks) | CCD# being in anomalous state | MOS1 | MOS2 |
|---------------------|------------------|--------------------|------------------------------|------|------|
| 0111850201          | 2001-06-16       | 68.6               | -                            | -    | -    |
| 0165770101          | 2004-08-04       | 67.9               | -                            | -    | -    |
| 0165770201          | 2004-08-06       | 68.9               | -                            | -    | -    |
| 0212090201          | 2005-01-24       | 30.4               | -                            | 5    | -    |
| 0310190101          | 2005-06-19       | 47.0               | 6                            | 5    | 5    |
| 0310190201          | 2005-06-25       | 49.5               | 6                            | 5    | 5    |
| 0310190501          | 2005-08-04       | 47.5               | 4.6                          | 5    | 5    |

one might expect that the X-ray photons obtained from the region A, B and C should be dominated by instrument background and the unresolved cosmic background. Thus, according to the XMM-ESAS cookbook, we constructed the model with eight components to explain the spectra: (1)Gauss + (2)Gauss + (3)APEC + (4)Abs*APEC + (5)Abs*APEC + (6)Abs*Pow + (7)Gauss + (8)Abs*BB. The first two gaussian (Gauss) components are to account for the Al Kα (E∼1.49 keV) and Si Kα (E∼1.75 keV) instrumental emission lines, respectively [14]. The third APEC component represents the plasma emission from the Local Hot Bubble or heliosphere. The fourth and fifth Abs*APEC components are the absorbed plasma emission that represent the emission from the clusters or intergalactic medium, and the hot plasma from unresolved component such as that of AGN, respectively. The sixth absorbed power-law component (Abs*Pow) is used to explain the unresolved point source such as X-ray binaries or AGN.
The seventh gaussian component is used to account for the line-like feature obviously seen in the spectra at $E \approx 0.56$ keV (see figure 1 (b)). Finally, the eighth absorbed blackbody component ($\text{ABS}^*\text{BB}$) is used to represent the extra, thermal-like emission from any other components, including electron/positron pair halo (if exist). In addition to this, the broken power-law were also add to the model to account for the residue of soft photon contamination which cannot remove completely.

All 12 spectra were fitted simultaneously to get the best statistical constraint of fitted parameters. In fact, we also add the constant component to the model to allow for a small difference between MOS1 and MOS2 data (given that the detectors are not perfectly identical), and also for normalising the data obtained from region A, B and C. The spectral fitting result are illustrated in table 2 and the right panel of figure 1. We note the that the fitting value obtained from all spectra are well consistent and, here, we show only the fitting results obtained from the region A of MOS1 which were not affected by anomalous state. From figure 1, it is obvious that the model could explain well the data even though the reduced $\chi^2$ value of 1.11 seems to be a little higher than unity; in fact, since all spectra are fitted simultaneously, the high number of spectral bins (6279 bins) could lead to this results and we regard this as the statistical acceptable results. In addition, as all best fitting parameters of the component 1, 2, 3, 4, 5 and 6 reported in table 2 are broadly consistent with the values suggested in the XMM-ESAS cookbook, here, we will skip discussing further the values of these parameters (albeit the upper bound temperature of the fifth component seems to be higher than that we expect). In case of the gaussian component (7) added to the model to improve the fit, although the physical origin is still unclear whether it arise from the instruments or the cosmic background, we regard that adding this component does not affect the detection of the pair halo since the spectral energy distribution of the halo are thermal-like rather than the line-like [6].

Table 2. Fitting results of region A spectrum obtained from MOS1.

| Model component (parameter) | Value (unit) |
|-----------------------------|--------------|
| (1) GAUSS (line energy)     | 1.49 (keV)   |
| (2) GAUSS (line energy)     | 1.75 (keV)   |
| (3) APEC (temperature)      | 0.32 ± 0.01 (keV) |
| (4) ABS*APEC (temperature)  | 0.27$^{+0.03}_{-0.04}$ (keV) |
| (5) ABS*APEC (temperature)  | $\leq 2.49$ (keV) |
| (6) ABS*POW (photon index) | 1.18$^{+0.03}_{-0.01}$ |
| (7) GAUSS (line energy)     | 0.56 (keV)   |
| (8ABS*BB (temperature)      | $\geq 2.21$ (keV) |
| (8ABS*BB (log flux)         | $-12.89^{+0.04}_{-0.14}$ (erg s$^{-1}$ cm$^{-2}$) |
| $\chi^2$ / degree of freedom | 6762.92/6103 |

As defined in the model, the absorbed blackbody component is used to represent the extra unresolved thermal-like emission that might have not been detected yet, including the pair halo emission. Thus, the detected blackbody-like flux of $\approx 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ could imply that at least, there might be the excess photons that could not be explained by the known components in the literatures. However, one might not be surprised to see the excess photons since, mathematically, adding more component is simply the increment of free parameters. Thus we check whether this component is statistical preferred using F-statistic; adding the blackbody
component improve the $\chi^2$ by $\sim 20$ for four degree of freedom losing, corresponding to 1-F probability of 99.79% (the probability that adding the component help to improve the fit). Therefore, it is unlikely that the flux detected is spurious.

The next question is that if the flux is genuine, can it be the contamination from the nearby object In fact, the nearest, bright source in our case is the blazar H1426+428. Although the central blazar region were removed from our analysis, as the source is very bright, some fraction of the blazar point spread function wing might affect our spectra, especially that of the region A, causing the contamination. We simply check the level of blazar contamination on our spectra by estimating the fraction of the blazar flux falling into our analysing regions. From the XMM-Newton user handbook [15], $\lesssim 1\%$ of point source flux would contribute to the region at angular radius $>0.04^\circ$ off from the source centre. Assuming that the flux of the blazar H1426+428 is $5.1 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ [16] and the inner radius of the region A is $0.09^\circ$ off from the source centre, so much less than $5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ blazar flux could contribute to the region A, B and C, and so we regard that this contamination should not dominate the emission in our analysing region.

Thus, if the detected excess flux is genuine and not dominated by the blazar emission, we might argue that the flux (at least some fraction) could arise from the pair halo emission of the blazar H1426+428. In fact, it is theoretically predicted that the spectral energy distribution of halos would seem nearly as the thermal-like emission [6], so that it is reasonable to represent the halo emission using the blackbody component. Moreover, our simulations (Eungwanichayapant et al. in prep.) show that the flux of H1426+428 halo generated from the seed blazar gamma ray energy of $\sim 70 - 100$ TeV surrounded by $\sim 1000$ nG ambient magnetic field could be in the order of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$, broadly consistent with our detection. However, there are still caveats with this interpretation. In fact, analysing the XMM-Newton background is the complicated tasks and need to perform very carefully (see [17] and references therein). In this work, as we follow the standard steps for analysing the data, we regard this as the first order approximation; the deeper analyses which examine every model components carefully are required in the future work to confirm the results. In addition, using the blackbody component to represent the halo emission might be at risk of misinterpretation since the thermal emission is one of the common emissions of astronomical objects. In fact, the detected thermal-like emission might be the combined emissions from many types of astronomical objects, including the pair halo. Thus, as discussed above, one must carefully examine the model components before interpret the emission as pair halo.

4. Conclusion

In this work, we analysed the X-ray data obtained from the areas around the blazar H1426+428 in order to search for the pair halo emission. Twelve good quality spectra had been created from seven observations of the blazar H1426+428. We modeled the spectra using eight components model which were accounted for all instrument backgrounds, unresolved cosmic backgrounds and the extra pair halo component. The excess flux of $\approx 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ has been detected and we discuss the possibility whether this flux could be intrinsic to the halo emission. We regard that the results are an first order approximation; the further analysis are required to confirm this.

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