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X-ray spectral model from clumpy torus and its application to Circinus galaxy

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Abstract. We construct an X-ray spectral model for the clumpy torus in an active galactic nucleus (AGN), utilizing the Monte Carlo simulation for Astrophysics and Cosmology framework (MONACO: Odaka *et al.* 2016). The geometry of the torus is the same as that in Nenkova *et al.* (2008), which assumes a power law distribution of clumps in the radial direction and a normal distribution in the elevation direction. We apply our model to the broadband X-ray spectrum of the Circinus galaxy observed with *XMM-Newton*, *Suzaku*, and *NuSTAR*. Our model can well reproduce the observed X-ray spectrum, yielding a hydrogen column density along the line-of-sight $N_{\rm H}^{\rm LOS} = 4.86^{+0.07}_{-0.04} \times 10^{24}$ cm^{-2} and a torus angular width $\sigma = 14.7^{+0.44}_{-0.39}$ degree.

Keywords. galaxies: active nuclei, galaxies: X-ray

1. Introduction

In the unified model framework, the obscuring matter in an active galactic nuclei, i.e. accreting supermassive black hole (SMBH) Antonucci 1993; Urry & Padovani 1995; Ramos Almeida & Ricci 2017), consists of gas and dust distributed in a toroidal shape. This "torus" is likely to play an important role in AGN feeding because the torus is a mass reservoir linking the host galaxy and the SMBH. Thus, elucidating the torus structure is essential to understand the mechanisms of the co-evolution between the host galaxy and SMBH (Kormendy & Ho 2013). Nevertheless, many of basic properties of AGN tori still remain unclear.

Many observations indicate that AGN tori must be composed of dusty clumps rather than of smooth gas (Krolik & Begelman 1988). In the infrared band, Nenkova *et al.* (2008) constructed spectral model from clumpy tori. They assumed a power law distribution of clumps in the radial direction and normal distribution in the elevation direction. This CLUMPY model has been successfully applied to the infrared spectra of nearby AGNs (Ramos Almeida & Ricci 2017).

X-ray observations are a powerful tool to investigate the torus structure. This is because X-rays can trace all matter including gas and dust at various physical conditions. It is only recently that X-ray spectral models for the clumpy torus have been developed (Liu & Li 2014; Furui *et al.* 2016. We construct a new X-ray clumpy torus model designated as "XCLUMPY", by adopting the same geometry of clump distribution as that of the CLUMPY model in the infrared band (Nenkova *et al.* 2008). This enables us to directly compare the results obtained from the infrared and X-ray and to which constrain the spatial distribution of dust and that of all matter, respectively.

2. Results and Discussion

We apply the XCLUMPY model to the broadband X-ray spectrum of the Circinus galaxy. This is because the Circinus galaxy is one of the closest (4.2 Mpc) obscured AGNs and is an ideal target for investigating the torus structure. *Suzaku* observed the Circinus

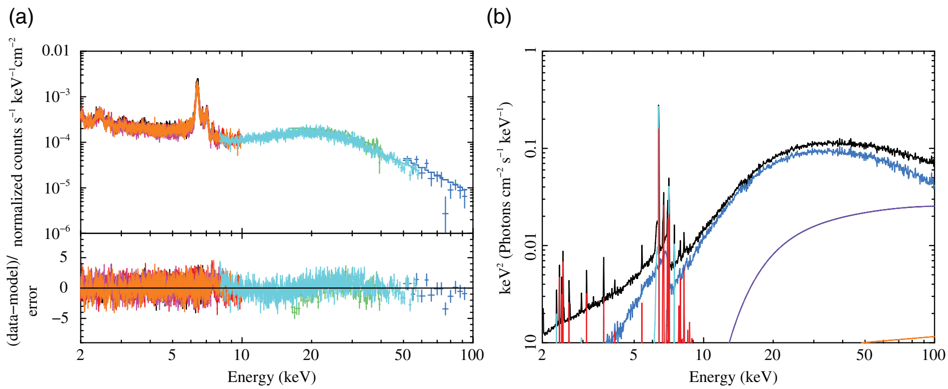

Figure 1. Left: folded X-ray spectra fitted with the XCLUMPY model. Right: best-fitting model. Left: Black crosses: *Suzaku*/BIXIS. Red crosses: *Suzaku*/FIXIS. Green crosses: *Suzaku*/PIN. Blue crosses: *Suzaku*/GSO. Pink crosses: *XMM-Newton*/EPN. Orange crosses: *XMM-Newton*/MOS. Light blue crosses: *NuSTAR*/FPMs. Right: Black line: total. Purple line: direct component. Blue line: reflection component from the torus. Light blue lines: emission line from the torus. Orange line: contamination from the CGX1. Red lines: contamination from the CGX2.

galaxy in 2006 July. Simultaneous observations with *XMM-Newton* and *NuSTAR* were performed in 2013 February. We collected X-ray data from the archive.

Our model can well reproduce the broadband X-ray spectra observed with the three satellites. Figure 1 shows the (a) folded X-ray spectra and (b) best-fitting model. We obtain the hydrogen column density along the line-of-sight $N_{\rm H} = 4.86^{+0.07}_{-0.04} \times 10^{24}$ cm^{-2} and torus angular width $\sigma = 14.7^{+0.44}_{-0.39}$ degree. Our measurement of the hydrogen column density is consistent with the one obtained by Arévalo *et al.* (2014). They analyzed the simultaneous *XMM-Newton* and *NuSTAR* observation data with the MYTorus model (Murphy & Yaqoob 2009).

We also compare the torus parameters obtained from the X-ray with those from infrared spectroscopy. The torus angular width obtained from the infrared data ($\sigma = 65^{+2}_{-5}$ degree: Ichikawa *et al.* 2015) is much larger than the X-ray results ($\sigma = 14.7^{+0.44}_{-0.39}$ degree). This can be explained by the presence of dusty polar outflow observed in the infrared interfere-metric observations (Stalevski *et al.* 2017), which makes the distribution of dust wider than that of gas.

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