Abstract

Observational evidence has clearly indicated the presence of multiple kinds of X-ray absorbers in active galactic nuclei (AGNs), e.g., warm absorbers, ultra-fast outflows (UFOs), and clumpy absorbers. The physical origins of these absorbers have been vigorously studied. For example, some radiation-magnetohydrodynamic simulations have suggested that the hot and strong accretion disk wind gets unstable far from the central region and turns into fragmented gas clumps. These inner wind and outer clumps may be actually observed as the UFOs and the clumpy absorbers, respectively. However, it is challenging to observationally place constraints on the origin of the UFOs and clumpy absorbers due to complicated spectral variations.

In order to resolve such parameter degeneracy of the clumpy absorbers and other spectral components, we have developed a novel technique called "spectral-ratio model fitting". Taking the spectral ratios of the intensity-sliced spectra enables us to make the spectral variations due to partial absorbers noticeable, by canceling out the less time-variable continuum and other absorption components such as warm absorbers.

We systematically applied this method to several Seyfert 1 galaxies to constrain the outflowing velocity of the clumpy absorbers and search for a plausible origin of the outflow and clumps. We found that the spectral-ratio fitting method requires certain conditions to effectively constrain the clump velocities: First, sufficient X-ray photon statistics and time variability are required. In addition, the key to disentangling the parameter degeneracy and deriving reliable outflow velocity of the X-ray absorbers is the appearance of the dip/cliff structure in the spectral ratios. The dip structure appears only when the spectral variation is caused by a change in the clumpy absorbers and when their parameters (column density $N_{\rm H}$ and ionization parameter ξ) are within a specific range. When all of these conditions are satisfied, we can constrain not only $N_{\rm H}$ and ξ but also the clump velocities.

For all the sources where the dip structures were recognized, we found that the soft spectral variation is mostly explained by changes in the covering fraction of the mildly-ionized clumpy absorbers with constant $N_{\rm H}$ and ξ. We found that the partial covering fraction is smaller and the normalization is higher as the X-ray flux increases. The determined outflow velocities of the partial absorber are unexpectedly fast and even comparable to those of the UFOs reported in previous studies. Furthermore, the velocity tends to be higher with increasing X-ray flux, which has been confirmed by a model-independent study of the most actively observed target IRAS 13224−3809. Based on the Markov Chain Monte Carlo calculation, we found that the outflow velocity is determined independently, not correlated with other parameters. These findings support the idea that both the UFOs and clumps are radiatively driven and share the same origin, as suggested in previous simulation studies.

The outflowing clumpy model also provides a plausible explanation of the energy spectra. Previous spectral studies of IRAS 13224−3809 and 1H 0707−495 using conventional models required a strong unexplained absorption edge around 1 keV. Our model naturally explains this residual structure due to blue shifts of the absorption edge/line energies of the outflowing clumpy absorbers.

Comparing the velocities of the UFOs and the clumps, we have found that the clump velocities can be comparable to or even faster than the UFO velocity. We have also found that the clump velocity increase trend with the flux is steeper than that of the UFOs.

Assuming that the UV–X-ray flux variation contributes to the increase in the kinetic energy of the disk wind, we examined whether only the flux increase can account for the velocity increase of the UFOs and the clumps. Consequently, whereas the UFO velocity increase trend is consistent with being driven by the UV-dominant continuum radiation, the clump velocity increase trend is not explained only by the continuum-driven scenario. This result suggests the possibility that, in addition to the continuum-driven mechanism, the line-driven mechanism contributes to the acceleration of the clumpy absorbers. In fact, while the UFO absorbers with $\log \xi \sim 4$ are highly ionized and transparent in the UV and soft X-ray energy ranges, the clumpy absorbers are mildly ionized at $\log \xi \sim 2.7$, and opaque to most UV and soft X-ray line emission.

We have found that the ionization state of the clumpy absorbers is always $\log \xi \sim 2.7$ regardless of the targets and flux levels. According to previous simulation studies, radiation hydrodynamic instability works only at a certain opacity, i.e., a certain ξ, to generate gas clumps. Therefore, the constant ξ of the clumpy absorbers is consistent with the instability scenario.