論文要旨

Study of black hole spin of Cyg X-1 with the X-ray spectral/timing analysis

X 線のスペクトル／タイミング解析による白鳥座 X-1 のブラックホールスピンの研究

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Measuring black hole spin (rotation of black hole) is important in order to understand the relativistic jet seen from the accretion flow. However, unlike mass, spin is difficult to determine as it only affects the spacetime properties very close to the black hole. There are three potential methods to estimate black hole spin. Two of them use the spin-dependence of the last stable circular orbit around the black hole as a diagnostic. This minimum radius leads to the maximum temperature and the highest luminosity of the disk emission. It also gives the fastest orbital velocity and strongest gravity which together sculpt the profile of the fluorescent iron line emission. The other proposed method instead uses the characteristic fast variability features (low and high frequency quasi-periodic oscillations: QPOs), interpreting these as the spin-dependent relativistic precession timescales (Lense-Thirring, and radial/vertical oscillation or Lense-Thirring and vertical/breathing mode oscillations). Black hole binaries are very bright, and thus, the statistical quality of the data is extremely good, giving small uncertainties on the derived spin in all methods. However, there are also systematic uncertainties, which are much less easy to quantify, but it is important because one object where all three techniques can be used gives three different spin values.

Clearly it is important to know which measurements are the most robust, and this depends on the black hole spectrum. Spectra which are dominated by the disk emission can give the same inner disk radius (so the same spin) for different mass accretion rates. However, the same radius is not always derived when the high-energy tail exists in the X-ray spectrum with more than $\sim 20\%$ of the total power. Therefore, robust spin estimation from disk continuum fitting requires that the spectrum is disk dominated. Conversely, the high-energy tail is required for reflection in order to have harder X-ray emission illu-

minating the disk. Unlike the disk continuum, the iron line and its associated reflected continuum are only a small fraction of the total flux, so a stronger tail gives better statistics to enable the small (5-10%) iron line to be constrained against the continuum. Unlike disk continuum fitting, the shape of the reflected emission does not depend on the distance to the source nor the black hole mass, which are sometimes poorly known. However, the reflected shape is dependent on more free parameters than that of the standard disk continuum model.

Using the fast timing QPO features then seems to offer a more model-independent way to constrain black hole spin of the galactic binary systems. However, while the timing features are independent of the spectral modeling, they are not independent of the specific QPO model assumed. Observational evidence in favor of a Lense-Thirring (vertical) precession origin for the low frequency QPO are accumulated, but the frequency depends on both spin and radius of the precessing material rather than spin alone. Combining this with that the high frequency QPOs potentially breaks this degeneracy, the spin value obtained depends on which high frequency oscillation mode is assumed to produce them, and this is not yet clear.

Thus we see observationally that the disk continuum fits can give robust results, but only for the subset of data where the spectra are disk-dominated. This is an issue for disk continuum fitting in Cyg X-1 as it never goes to a state where the high-eenrgy tail is very low. Thus the very high spin of $a > 0.9$ measured in this system by disk continuum fitting, could depend on how the high-energy tail is modeled. Here we show new data from the Suzaku X-ray satellite where the high-energy tail is the weakest ever observed in Cyg X-1. We show that this spectrum gives the same high spin value as previous soft state datasets with stronger tail when we fit with the same continuum model of a standard disk and Compton tail from electrons with a non-thermal electron distribution. However, we get a significantly better fit for lower black hole spin if we allow an additional component between the disk and high energy Comptonisation. This emission carries only $\sim 10\%$ of the total luminosity, and indicates a region which is optically thick, and fairly cooler than Comptonization corona, but hotter than the majority of the disk emission, and clearly thermal. This could be due to a hybrid thermal/non-thermal electron distribution, but the high optical depth more naturally connects this to the disk. This could be connected to a changing accretion disk structure during transitions, where the truncated disk models predict that the inner cool disk is reforming from the hot flow.

We show that the models with an additional thermal component is significantly better to explain the spectrum and confirmed the consistency by timing analysis. Fundamentally, disk continuum fitting assumes that the disk vertical structure is well described by the disk equations. This may not be true during the major hard-soft spectral transition, or whenever the inner disk is threaded by significant magnetic field.