論文内容の要旨

論文題目

”Multi-Epoch Measurements of Inner Radii of Dust Tori in the Nearby Seyfert 1 Galaxies”

(近傍 1 型セイファート銀河におけるダストトーラス内縁半径の長期計測)

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Active Galactic Nuclei (AGNs) are known as one of the brightest object in the universe. The energy source of their whole enormous emission is supposed to be generated by central super massive black hole and accreting material onto it. In the context of the standard unified model, the structure of AGN is explained as below. First, the accreting gas around the super massive black hole form an accretion disk at 10^4 K or higher temperature, transferring its gravitational potential energy into thermal emission radiated in wavelength range from optical to X-ray. Next, the super massive black hole and accretion disk is surrounded by gas clouds which move at high velocity more than a few 10^3km/s. The gas clouds are ionized by UV flux from accretion disk and radiate emission lines when recombination occurs, which are broadened due to high velocity motion of the clouds. Then, at the outer region of the broad emission line region (BLR), there distribute optically thick dust. The dust obstruct line of sight from a certain direction to the accretion disk or the BLR. As a result of the obscuration, two types of spectrum of AGN with or without broad emission lines (BELs) could be observed (Antonucci 1993). Each type of AGN is called as type 1 and type 2 AGN respectively.

Now consider about relationship of accretion disk and surrounding dust. The dust around BLR not only obscure the central region of AGN but also radiate thermal emission, warmed up by UV/optical emission from accretion disk. The highest temperature of warmed dust is limited by sublimation temperature of dust grains which is about 1800K for graphite grains. Thus the spectrum of thermal emission by dust should have its peak at near-infrared (NIR) wavelength region.

Meanwhile, sublimation of dust by UV/optical flux from accretion disk leads to hollow distribution of dust, like a torus, because the dust grains at close region to accretion disk reach its sublimation temperature and could not survive. The sublimation radius of dust $r_{\rm sub}$ should be proportional to the square root of UV/optical luminosity $L_{\rm UV/opt}$, or $r_{\rm sub} \propto L_{\rm UV/opt}^{0.5}$, because UV/optical flux is diluted with increasing the distance from accretion disk. In other words, the innermost radius of dust torus is determined by UV/optical luminosity of accretion disk.

With such torus-like structure of dust and thermal reprocessing of UV/optical emission into NIR emission, it is expected that variation of UV/optical flux is followed by NIR flux variation with a certain time delay corresponding to light travel time between accretion disk and innermost region of dust torus. Such phenomena called dust reverberation have been actually observed in a number of AGNs (e.g. Clavel et al. 1989; Glass 1992) and given a strong support to the unified model of AGN.

Inversely, using dust reverberation model describe above, intrinsic UV/optical luminosity of accretion disk could be obtained from observed time delay between optical and NIR variation with an appropriate dust sublimation model. The derived intrinsic luminosity could be converted into luminosity distance of AGNs without assuming any cosmological parameter, thus the time delay between UV/optical variation and NIR variation at AGNs could be available as a new distance indicator. Aiming at establishment of this new distance indicator, Multicolor AGN Monitoring project (MAGNUM, Yoshii 2002; Yoshii et al. 2003) have started photometric monitoring of AGNs at year 2000. They succeeded in obtaining the most intensive and accurate light curve of tens of AGNs in wide wavelength range from optical and NIR after continuing the photometric monitoring with a 2m telescope specialized to the purpose for 8 years. For a number of the target AGNs, they estimated the time delay between optical and NIR from the light curves employing the Cross Correlation function (CCF) analysis. The derived time delays were confirmed to strongly correlate with the optical luminosity as expected from the dust reverberation model (Minezaki et al. 2004). The also confirmed that the inner region of dust torus were located at just outer region of BLR, comparing the time delay between optical and NIR variation with that between optical continuum and broad emission line (Suganuma et al. 2006). These results observationally supported the dust torus structure in the unified model of AGN. With accurate and intensive light curves of MAGNUM project, Tomita (2005) also succeeded in extracting accretion disk flux in NIR band and conclude that the shape of spectral energy distribution (SED) of accretion disk flux could be represented as typically $\alpha = 0.0$–0.5 in a form of power law index of the spectrum.

In this dissertation, I derived the time delays between optical and near-infrared variation of 17 Nearby Seyfert 1 galaxies with photometric monitoring data of MAGNUM project. One of the aim of this study is to obtain the largest homogeneous sample of the inner radii of dust tori ever before. With this sample, it is possible to confirm the generality of the dust reverberation or basic structure of dust in AGN observationally. This is also necessary for establishment of new distance indicator by dust reverberation.

Besides the estimation of time delays in large number of AGNs, I also payed attention to longevity of the monitoring program of MAGNUM and estimated the time delay for each plural variation features on the light curves of an individual AGN. Although it has been showed that the time delays or inner radii of dust tori were correlated with the optical luminosity of AGN, it have not been confirmed that the radius of dust torus would be vary or not with the UV/optical variation in an individual AGN. By multi-epoch measurements of the time delay, the existence of variation of the time delay in individual AGN could be discussed. To investigate the response of time delay against the optical variation would give important suggestions on characteristics of the dust in AGN central region.

For these aims, I derived the light curves in UBVIJHK band for the 17 nearby Seyfert galaxies after data reduction and aperture photometry. In the photometric aperture, contaminating flux from host galaxies or narrow emission lines were included. These component disturb accurate estimation of the optical luminosity of accretion disk, so I subtract these component. Besides the contaminating flux above, the flux from outer and low temperature region of accretion disk is contained in NIR bands (Tomita 2005). The NIR flux from accretion disk is supposed to be synchronized rather to optical flux from accretion disk than thermal dust flux, so it also disturb accurate estimation of inner radius of dust torus. I subtracted the contamination from all Seyfert galaxies assuming the power law index of accretion disk flux $\alpha = 0.0$.

Then, to estimate inner radius of dust torus in nearby Seyfert galaxies,I employed CCF analysis. In CCF analysis, it is necessary to interpolate discrete observed light curve to obtain a flux pair at the same observational time. Suganuma et al. (2006) suggested two interpolation method of bi-directional (BI) interpolation method and equal sampling (ES) method, and I employed the BI method because the method weighted more actually observed data than simulated data. The error of the time delay were estimated by Monte-Carlo simulation. For the estimation of inner radius of dust torus, I selected light curves in V band as an indicator of UV/optical flux from accretion disk and that in K band as thermal dust flux.

As a result of CCF analysis for light curves obtained by MAGNUM project, 49 of the time delay could be derived with 17 nearby Seyfert 1 galaxies. Figure showed strong correlation of these time delays, which indicated the inner radii of dust tori, with absolute magnitude in V band, which indicated the UV/optical luminosity of accretion disk. This is the first time to show the correlation with such large and homogeneous sample. The correlation derived here showed good agreement with scaling law of the time delay $\Delta t \propto L_{\rm UV/opt}^{0.5}$ predicted by dust sublimation model in the wide range of absolute magnitudes of AGNs in V band $M_{\rm V}$ from -15 to -22. By generality of the correlation, it is confirmed that the basic property concerning dust sublimation in AGN is almost common in nearby Seyfert 1 galaxies along the wide range of UV/optical luminosity, that is for example, the dust grain size or SED of dust warming flux. I also compared the derived 49 inner radii of dust tori with the BLR size in Bentz et al. (2006). As Suganuma et al. (2006) showed, the inner radii of dust tori were distributed just outside of outer region of BLR. The drawing of unified model were again confirmed observationally with large homogeneous sample at the point of radial distribution of BLR and dust torus.

On the other hand, paying attention to the multi-epoch measurements of the time delay in an individual AGN, the time delay seemed to be variable beyond its error. Especially NGC4151 and a few Seyfert galaxies showed apparent variation of Δt beyond the 3σs. This is the first detection of the variation of the inner radius of dust torus with such clarity. The most rapid variation of the time delay of NGC 4151 was occurred during 309 days, and amount of variation of the time delay corresponded to a light-travel distance of 6.35×10^{11}km. If such a decrease of inner radius of dust torus would occur with redistribution of dust grains supplied from outer regions of, the infall velocity would be 2.4×10^4km/s. This seems highly unlikely when we compare this infall velocity with a few 10^3km/s for the velocity dispersion of BLR clouds which exist just near the inner radius of dust torus. Consequently, it is concluded that reformation of dust grains did occur in the central region where they had been sublimated.

Following the time-changing track of the time delay and $M_{\rm V}$ of NGC4151, it also seemed that they did not always follow the general regression line of $\Delta t \propto L_{\rm UV/opt}^{0.5}$, though they showed generally strong correlation with other Seyfert galaxies. If dust reformation or sublimation occur right after variation in UV/optical flux, the track would be drawn along the same direction of the general regression line. This would implicate that the dust sublimation or reformation is occur with a certain amount of time lag behind the UV/optical variation due to, for instance, clumpy and self-shielding structure of dust torus.

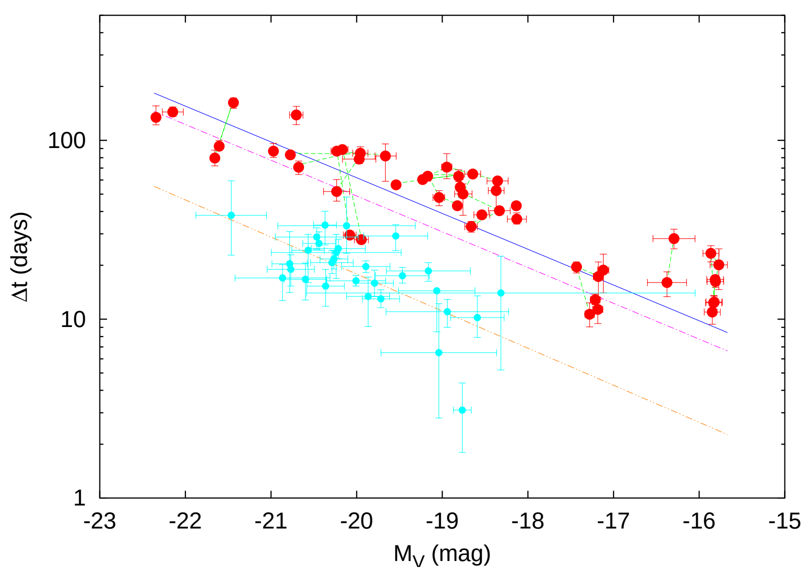

図 1: General correlation of Δt and $M_{\rm V}$ for nearby Seyfert 1 galaxies. Red and large filled circles represent Δt for dust tori while cyan and small filled circles represent that for broad Hβ line in Bentz et al. (2006).