論文の内容の要旨

論文題目

Probing High Energy Phenomena in the Vicinity of Super-massive Black Holes with Millimeter VLBI
(ミリ波 VLBI による超巨大ブラックホール近傍における高エネルギー現象の観測的研究)

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In this thesis, we present three millimeter-VLBI studies with the VLBI Exploration of Radio Astrometry (VERA) and the Event Horizon Telescope (EHT) on (1) the Galactic Center Sgr A* and (2) the nearby radio galaxy M87, which harbor supermassive black holes with the largest and second largest angular sizes, as well as (3) the γ-ray blazar NRAO 530 during its large GeV γ-ray outburst. Our studies provide the unprecedented information on the structure and activities of the regions very close to supermassive black holes (SMBHs), as summerized below.

In the work (1) on Sgr A*, we performed long-term monitoring observations of Sgr A* with the Japanese VLBI array VERA at 7mm (i.e. 43 GHz) for three years to investigate relation between variations in the radio flux and the structural size in the vicinity of its SMBH and to probe a possible mechanism of its variability, all of which have been not well understood. We found a new kind of the radio flare in Sgr A* with a long duration at least longer than 7 days without obvious changes in its size. The duration of flare is much longer than typical cooling timescales of electrons emitting the radio wave, indicating changes in the steady state of Sgr A*. We found the mas-scale properties of the flare cannot be explained by changes in the mass accretion rate of the thermal accretion disk models for Sgr A*, requiring other mechanism to explain this flare.

In the work (2) on M87, we performed 1.3 mm (i.e. 230 GHz) VLBI observations of M87 with EHT during the enhanced very-high-energy (VHE) γ-ray state in 2012. We obtained following three results. (2-i) For the first time, we have acquired 1.3 mm VLBI interferometric phase information on M87 through measurement of closure phase, that is consistent with physically-motivated models. We found that future EHT observations can effectively distinguish physical models and also confirm a signature of the gravitational lensing in M87. (2-ii) The brightness temperature of the event-horizon-scale structure is broadly consistent with the peak brightness of the radio cores at 1-86 GHz located within 100 $R_{\rm s}$. A

simple analysis predicts the magnetic field profile inversely proportional to the distance from the jet for the M87 jet, which is expected by the toroidal-field-dominant conical jet. (2-iii) Our measurements, combined with results of multi-wavelength observations, favor a scenario in which the VHE region has an extended size of the VHE emission region of ~20-60 $R_{\rm s}$. It seems incompatible with many VHE models expecting the compact emission region of a few $R_{\rm s}$ for this VHE activity.

In the work (3) on NRAO 530, we performed 1.3 mm (i.e. 230 GHz) VLBI observations of NRAO 530 with EHT, six months after a large γ-ray flare at GeV band. The observed 1.3 mm structure is resolved into two components consisting of the core and a relatively extended jet component that is the most probable counter part of the GeV γ-ray flare. The position angle of the inner jet is in South-West direction, being considerably different from the larger-scales jet directed to the north. 7 mm observations with the Very Long Baseline Array at 7 mm reveal that the 7-mm counter part of this jet component moved to the north as well, requiring the highly curved trajectory in the inner jet on sub-parsec scales. This is the first example that a jet component related with γ-ray activities actually moves along a curved trajectory, as suggested in previous studies on the γ-ray activities in other blazars. The flaring component has a size of $\sim 140\ \mu$as $=$ 1304 ld, much larger than the upper limit size of $\lesssim$ 49 ld at the GeV flare. This requires apparent super-luminal expansion of the flare component on the framework of the widely accepted scenarios assuming the co-spatiality of broadband emission, giving a strong limit with a jet speed of $\beta > 0.988$, Lorentz factor of $\Gamma > 6.41$, viewing angle of $\theta < 5.77^{\circ}$ and Doppler factor of $\delta > 9.85$.

In summary, we obtained several unprecedented findings about the physical nature of the accretion flow and relativistic jet in the vicinity of SMBHs with millimeter VLBIs. All of the three works in this thesis demonstrate importance of the future mm-VLBI observations particularly with EHT to understand fundamental nature of the high energy phenomena in the vicinity of the SMBHs.