Very-high-energy gamma-ray observations of blazars with the MAGIC telescopes and performance study of the next-generation atmospheric Cherenkov telescope CTA-LST

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Active galactic nuclei (AGN) are believed to have a super massive black hole and a potential site of the cosmic-ray acceleration. In the unified AGN model, AGN have different observed properties depending on the viewing angle. Flat-spectrum radio quasar (FSRQ) is one of AGN types with a pair of relativistic jets and a rich photon field derived from a broad line region (BLR) and dusty torus (DT). One of the biggest mysteries is the location of the energy dissipation region where radiating particles are accelerated above sub-TeV in a relativistic jet. Locating the emission region is important not only to understand the relativistic jet structure but also to estimate the external photon property which can act as a target photon to produce neutrino via proton-photon interactions.

For a long time, the location of the emission region is thought to be inside BLR based on a fast variability of gamma-ray emission (scenario A). However, the recent gamma-ray observations tend to favor another scenario that the emission region is located outside BLR and inside DT (scenario B). The gamma-ray observations of FSRQ play a key role to constrain the location of the emission region because the gamma-ray spectrum has an imprint of the photon-photon absorption in a rich photon field. With a general assumption, very-high-energy (VHE) gamma-ray photons (>20 GeV) are impossible to escape beyond BLR. Thus, the detection of VHE gamma-ray signals supports scenario B. On the other hand, there are several models to explain the escape of VHE gamma ray with different BLR geometry. Therefore, the spectral features on the VHE gamma-ray band is essential to obtain key insights into the location of the gamma-ray emission region.

For this purpose, two approaches are taken in this thesis. The first approach is VHE gamma-ray observations of FSRQ with the current operational imaging atmospheric Cherenkov telescopes (IACT), and another approach is the development of the next-generation IACT for future observations of FSRQ with better sensitivity and a lower energy threshold (20 GeV). The low-energy threshold is helpful for the extragalactic gamma-ray source observations located at a large redshift because VHE gamma-ray photons are also absorbed by extragalactic background lights and the opacity is larger at a higher energy range.

First, VHE gamma-ray observations of FSRQ B1420+326 were performed with the MAGIC telescopes during a gamma-ray flare in 2020. B1420+326 is the eighth FSRQ discovered by ground-based telescopes in the VHE gamma-ray band as of the time of the detection. The clear detection of VHE gamma-ray signals from B1420+326 was confirmed with 13.1σ in 1.6 hours effective time on the night of January 20 2020. The integral flux of the flare is comparable to 15% Crab Unit above 100 GeV. The detection of VHE gamma-ray signal indicates that the location of the gamma-ray emission region is beyond the BLR. To confirm this picture, the modeling of multi-wavelength spectrum of B1420+326 was performed. As a result of the modeling, the spectrum of B1420+326 can be interpreted with a hybrid of electron synchrotron radiation, synchrotron-self Compton scattering and external inverse Compton scattering with infrared photons from DT. This modeling result also confirms the emission region is outside the BLR and inside the DT.

As the second approach, we have been developing the Large-Sized Telescope (LST) with a segmented mirror of 23 m diameter for the Cherenkov Telescope Array. The first LST (LST-1) was inaugurated in October 2018. First of all, low-level calibration procedures were developed to compensate for intrinsic features of analog memory GHz sampling chip DRS4 in the camera readout. The calibration procedures for the camera are separated into pedestal-voltage corrections and sampling time interval inhomogeneity corrections. After these waveform corrections, the noise level is comparable to 0.2 photoelectron level, charge resolution is below 5% at thousand photoelectron range, and time resolution is 0.4 ns with a calibration laser.

Second, analysis procedures, especially event reconstructions with machine learning, have been developed and the performance of the LST-1 was evaluated using Monte Carlo simulation data. In addition to the standard approach, a source-dependent approach has been developed for better analysis performance at low-energy range (<100 GeV). For this approach, additional parameters with an assumption of the expected point-source position are used as input parameters of machine learning. As a result, the energy resolution is 20—30% at 100 GeV and ~10% above TeV range, and the angular resolution is 0.1° at 100 GeV and 0.05° above a few TeV. For the particle classification, the source-dependent approach has a better segregation power below 100 GeV. Concerning the gamma-ray source detection sensitivity, it reaches 2% Crab Unit at 500 GeV.

Finally, the LST-1 performance was also evaluated with observational data. The first target is the Crab Nebula as the standard candle of VHE gamma-ray sources. From the Crab Nebula observations in 15.2 hours, gamma-ray signals were clearly detected with a significance above 50σ. The obtained spectral energy distribution above 40 GeV is comparable to one obtained with the MAGIC telescopes. To evaluate the performance at the low-energy range (<100 GeV), the LST-1 observed a bright gamma-ray flare from the blazar BL Lacertae. The total observation time was 1.8 hours and the LST-1 detected the bright gamma-ray signals with a significance of 35σ above 300 photoelectrons. The LST-1 obtained the spectrum above 20 GeV and the spectrum is consistent with one obtained with the MAGIC telescopes above 50 GeV. Even though the gamma-ray detection sensitivity below 100 GeV is worse than the MAGIC telescopes as expected, the low-energy threshold of 20 GeV with the LST-1 was confirmed. The gamma-ray flux level around 20 GeV is comparable to one obtained with *Fermi*-LAT and both spectra are smoothly connected.