Perseus in Sicily: From Black Hole to Cluster Outskirts
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Inflow and Outflow (Jets) in NGC 1275

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Abstract. NGC 1275 is one of the best targets to study the high energy emission mechanism in radio galaxies and the accretion flow properties using a young re-started jet 3C 84 as a prober of subpc-to-pc scale environment. In this proceeding, we review the observation results from a series of our VLBI observations and discuss on the origin of gamma-ray emission and accretion flow properties. We also briefly present the preliminary results from our recent ALMA observations.

Keywords. galaxies: active, galaxies: individual (NGC 1275), galaxies: jets

1. Introduction

The Perseus cluster is a nearby (z=0.017) cluster of galaxies and has been the subject of extensive research over years at all wavelengths. The cluster harbors the giant elliptical and radio galaxy NGC 1275 at its center, and this galaxy shows an intermittent jet activity in which the most recent activity started in ∼2005 (Abdo *et al.* (2009); Nagai *et al.* (2010); Suzuki *et al.* (2012)). This system is the brightest X-ray cluster of galaxies and best example of a prototypical "cooling core" cluster with a signature of the interaction between the jet and the intra-cluster medium (ICM) (e.g., Fabian *et al.* (2002)).

Strong time variability of the nucleus of NGC 1275 is observed at multiwavelengths from radio to γ-ray as well as the jet intermittency. In particular, this source shows a remarkable flux variation in γ-ray band (Dutson *et al.* (2014)). Since *Fermi* started to monitor this source, a monotonic increase of the γ-ray flux has been observed in addition to rapid time variation with a timescale of days-weeks. This long-term flux increase is not commonly observed in blazars, and thus it might give a hint to understand the γ-ray emission mechanism in non-blazar sources, which is still disputed.

The observed time variability indicates that the black hole accretion is time variable, and perhaps the accretion flow can be strongly inhomogeneous. It is suggested by numerical simulations of giant elliptical galaxies that the growth of thermal instabilities in the hot halo/cluster gas leads to the condensation of cold clouds and filaments (Gaspari *et al.* (2013)). As a result, the accretion flow from cluster scale to the central black hole is dominated by cold and chaotic accretion. A large amount of cold molecular gas is in fact observed in NGC 1275 in the form of filaments of CO gas on kpc scales (Lim *et al.* (2008)). However, it is not clear how the large-scale molecular gas is settling into the circumnuclear region because of the lack of spatial resolution in previous observations.

In this paper, we review our previous VLBI observations and present new ALMA observations to discuss on three open questions: i) What is the γ-ray emission mechanism?, ii) What is the accretion flow properties of NGC 1275?, iii) Is the cold accretion dominant within 10-100 pc scale around the nucleus?.

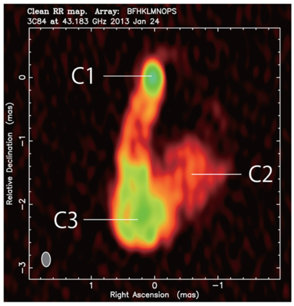

Figure 1. VLBI image of NGC 1275 (3C 84) on 2013 January 24.

2. Connection between Radio and γ-rays: A hint for the γ-ray emission mechanism

As we can see from the light curve available at the Submillimeter Array (SMA) and *Fermi*-LAT homepages (SMA: http://sma1.sma.hawaii.edu/callist/callist.html?plot=0319%2B415, *Fermi*: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/source/NGC_1275), both radio and γ-ray light curves have shown flux increases since the beginning of *Fermi* operation on the timescale of years. It was shown that the radio brightening was caused by the re-started jet activity in ∼2005 (Abdo *et al.* (2009); Nagai *et al.* (2010); Suzuki *et al.* (2012)). This likely indicates that the recent high flux level of γ-ray originates in the re-started jet activity. However, the correlation in radio and γ-ray light curves is not evident on shorter timescales. We can see several small flares in radio and γ-ray on the timescale of weeks-months, but no clear one-to-one correspondences has been observed for each flare (e.g., Nagai *et al.* (2012)).

The absence of radio counterpart of the γ-ray flare has been conventionally understood as the strong self-absorption of the flaring region in radio bands. Several authors attempted to do modeling the observed spectral energy distribution (SED) from radio to γ-ray using one-zone synchrotron self-Compton (SSC) model, and radio data were discarded because of the same reason. However, the large separation between two bumps of SED in ν-νF_ν plane cannot be well reproduced by one-zone SSC (see discussion by Tavecchio & Ghisellini (2008)) even if we discard the radio data. Following the discovery of limb-brightened structure in the subpc-scale jet (Nagai *et al.* (2014) and see Fig. 1), the SED modeling in the framework of the spine-layer scenario is adopted to NGC 1275 (Tavecchio & Ghisellini (2014)), which seems to rather reproduce the observed SED under the condition of the jet viewing angle of 18°. On the other hand, Fujita & Nagai (2017) discovered the counter jet component and derived the jet viewing angle of $65° \pm 16°$ from the apparent length ratio between the jet and counter jet. It seems that the observations do not favor the misaligned blazar model. One more complication is that the total flux density of the hotspot/lobe (C3) is comparable to that of the core (C1), and thus the SSC emission from C3 may not be negligible. This could be a reason that the SED cannot be explained by one-zone misaligned blazar model (see also discussion by Hodgson *et al.* (2018)). We should also keep in mind that the entire structure of C1+C2+C3 is very small (∼ 1 pc) and thus resides in the dense external photon fields from accretion disk and circumnuclear disk/torus. Inverse Compton upscattering of various surrounding photons can also contribute to the high energy emission of NGC 1275 (e.g., Stawarz *et al.* (2008)).

3. Accretion Flow Properties

The entire radio structure associated with the most recent restarted jet can be used as a prober of the environment in subpc to pc scales. Fujita & Nagai (2017) recently

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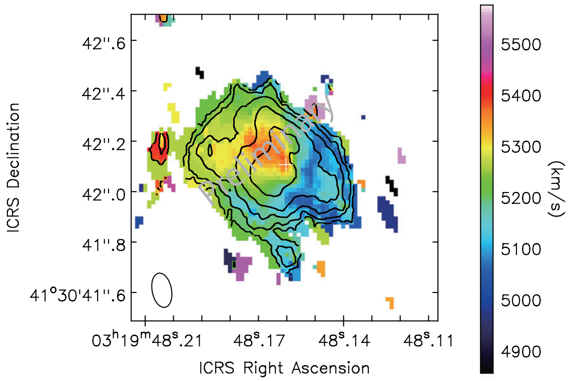

Figure 2. The contour of velocity integrated intensity overlaid on the velocity distribution of HCN(3-2) emission. The plus symbol in the image indicate the AGN position.

discovered the counter jet component at ~ 0.8 pc north of the core, which is presumably associated with the re-started jet activity in $\sim$2005. The counter jet component shows a strong inverted spectrum between 15 GHz and 43 GHz, which is similar spectral behavior observed in larger scale counter jet (Walker *et al.* (2000)). The most likely explanation for the inverted spectrum is free-free absorption. Walker *et al.* (2000) discussed that there is an accretion disk extending to the pc scales and that the ionized part of the accretion disk is responsible for the absorption. The observed absorption by Fujita & Nagai (2017) is likely caused by the further inner part of the accretion disk.

Fujita & Nagai (2017) found that the frequency dependence of the free-free absorption is $\tau_{\rm ff} \propto \nu^{-0.6}$, which is different from the theoretical expectation $\tau_{\rm ff} \propto \nu^{-2}$. They argued that the absorbing medium is highly inhomogeneous and that it consists of regions of $\tau_{\rm ff} \gg 1$ and $\tau_{\rm ff} \ll 1$.

Nagai *et al.* (2017) reported the abrupt change in the hotspot position as well as the enhancement of the polarized emission by VLBI observations. The change in the hotspot position can be caused by the interaction between the jet and inhomogeneous/clumpy ambient medium. They also reported the detection of Faraday rotation. The derived rotation measure (RM) is at most $(6.3 \pm 1.9) \times 10^5$ rad m^{-2}, which shows an agreement with the RM reported by the CARMA and SMA observations within a factor of 2 (Plambeck *et al.* (2014)). One possible origin of the Faraday rotation is the accretion flow. However, Nagai *et al.* (2017) discussed that similar RM values between the VLBI observations and the CARMA/SMA observations cannot be consistently explained by the spherical accretion flow with a power-law profile, such as radiatively inefficient accretion flow (RIAF), which is the favored model for the low luminosity AGNs such as NGC 1275. They claimed that the dense clump could be responsible for the observed Faraday rotation by VLBI observations.

Overall results indicate that the subpc-pc scale environment can be quite inhomogeneous and is not consistent with the RIAF-like quasi-spherical accretion flow.

4. Cold Accretion

We recently observed NGC 1275 with ALMA to study the cold gas properties of circumnuclear region in 10-100 pc scale. We detected CO(2-1), HCN(3-2), and HCO$^+$(3-2) emissions in this region. Figure 2 shows the velocity integrated intensity overlaid on the velocity distribution of HCN(3-2) emission. The emission clearly shows a central concentration at the AGN position, which suggests that the cold gas is still abundant within the central ~ 10 pc. The velocity gradient is observed in the position angle of ~ 70 deg. Both

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the morphology and kinematic structure indicate the rotating disk around the AGN position, yet the disk structure is not smooth nor uniform. The velocity gradient is roughly perpendicular to the subpc-scale jet axis (Giovannini *et al.* (2018), see also Fig. 1). This may suggest that the molecular gas disk is physically connected to the accretion disk at further inner region, which is responsible for the jet launching, possibly changing its form from the cold molecular gas to ionized gas. The cold accretion might be a dominant mechanism to characterize the AGN activity of NGC 1275.

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