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Circumnuclear multi-phase gas around nearby AGNs investigated by ALMA

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Abstract. Since the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), more attention has been paid on the $\lesssim$100 pc scale circumnuclear disk (CND) to reveal feeding and feedback processes of active galactic nuclei (AGNs). By using cold molecular CO and atomic C^0 emission line observations, we have revealed that there are multi-component gas dynamical flows around the AGN of the Circinus galaxy, which may explain the physical origin of the AGN torus. In the luminous Seyfert galaxy NGC 7469, we found that [CI](1–0) line is extraordinary bright relative to CO lines (for example $J = 2-1$), manifesting the physical/chemical influence of the AGN on the surrounding gas in the form of X-ray dominated region (XDR).

Keywords. galaxies: active, galaxies: Seyfert, galaxies: evolution, ISM: evolution

1. Introduction

Almost thirty years have passed since the advent of the active galactic nucleus (AGN) torus paradigm (Antonucci 1993). In this scheme, AGN is surrounded by a dusty/gaseous donut-like structure, along the hole of which we can directly see the highly ionized broad line region, whereas our line-of-sight is blocked when we look at the core from its side. This scheme explains many observational features of AGNs (e.g., Ramos Almeida & Ricci 2017), however, its physical origin remains unclear. Wada (2012) attributes this origin to multi-phase gas dynamics in the circumnuclear disk (CND) and AGN radiation-driven winds, based on high resolution hydrodynamic simulations that also incorporate X-ray dominated region (XDR) chemistry (Maloney *et al.* 1996). In their simulations, dense molecular gas is confined in the mid-plane of the disk. Hot ionized gas is predominantly seen in AGN-driven outflows. Atomic gas is intermediate: a fraction of this phase gas is in warm outflows, part of which eventually falls back to the disk due to the disk gravity (= failed wind). The circulation of gas inflow (through the disk mid-plane), outflow, and failed wind (fountain) causes turbulence, which naturally forms a geometrically thick structure, i.e., torus. Although all of these occur at the central < 100 pc region of AGNs, now the Atacama Large Millimeter/submillimeter Array (ALMA) enables us to probe that compact region and test the above predictions. Here, we present two high resolution ALMA programs toward nearby Seyfert galaxies, namely the Circinus galaxy and NGC 7469. In these experiments, we observed both molecular CO lines and atomic [CI](1–0) line, so that we can probe both the dense molecular and diffuse atomic parts of the CND.

2. High resolution multi-phase gas dynamics in the Circinus galaxy

In our ALMA Cycle 4 observation, we successfully detected CO(3–2) and [CI](1–0) line emission from the central region of the Circinus galaxy ($D = 4.2$ Mpc) at the spatial resolutions of $\sim$6$-$15 pc, as presented in Izumi *et al.* (2018). The line emission was bright

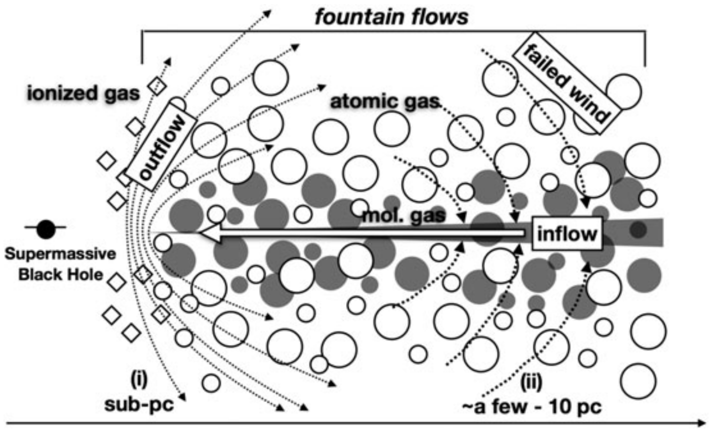

Figure 1. Our new picture of multi-phase AGN torus (modified from Izumi *et al.* 2018). Each phase gas preferentially traces different flows including inflows (molecular; filled circle), hot outflows (ionized; diamond), and warm outflows + failed winds (atomic; open circle), respectively.

at the innermost <100 pc region, manifesting the genuine existence of a massive CND. At the AGN position, we found that the spectral profiles of CO and [CI] are clearly different. The CO(3–2) shows a single Gaussian-like profile, which is usually seen in the CND-scale of nearby AGNs. On the other hand, the [CI](1–0) shows a triple Gaussian-like feature. The latter manifests the existence of atomic gas outflows. The estimated outflow velocity, however, does not exceed the escape velocity from the system. Hence at least part of the atomic outflow eventually falls back to the disk, i.e., failed wind. These are consistent with the predictions of the radiation-driven fountain torus model, which provides a key observational insight to understand the physical origin of AGN torus. A new dynamic picture of AGN torus based on our work is shown in Figure 1.

3. X-ray dominated region caught in the act in NGC 7469

To investigate potential AGN influence on the surrounding gas in the form of the XDR, we also observed multiple ^{12}CO lines (from $J = 1$–0 to 3–2), ^{13}CO(2–1), and [CI](1–0) emission toward the CND of the luminous type-1 Seyfert galaxy NGC 7469 ($D = 70.8$ Mpc) during ALMA Cycle 5. The CO lines are bright both in the CND and the surrounding starburst ring (SB ring; ∼1 kpc diameter), with two bright peaks on either side of the AGN. By contrast, the [CI](1–0) line is strongly peaked on the AGN. Consequently, the line brightness temperature ratio of [CI](1–0) to ^{13}CO(2–1) is ∼10 times higher around the AGN than at the SB ring. Our non local thermodynamic equilibrium simulations suggest that at least enhanced C^0/CO abundance ratio (∼10), as well as high gas temperature (>100−500 K) around the AGN relative to the starburst ring, are required to explain this line intensity enhancement. These physical and chemical features are consistent with the XDR model prediction that shows elevated C^0 abundance due to efficient dissociation of CO around AGNs (Maloney *et al.* 1996).

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