Publications of the Korean Astronomical Society
32: 175 ∼ 177, 2017 March

pISSN 1225-1534
eISSN 2287-6936
https://doi.org/10.5303/PKAS.2017.32.1.175

HIGHLY EXCITED CO LINES IN ACTIVE GALAXIES BOTH IN ABSORPTION AND IN EMISSION

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(Received June 16, 2015; Revised October 20, 2016; Accepted October 20, 2016)

ABSTRACT

In order to reveal physical conditions of molecular gas in active galaxies (active galaxies mean both starbursts and AGNs in this paper), we carried out systematic observations ($R = 19 \sim 120$) of CO fundamental band at 4.7 μm in absorption with *AKARI.* We also made follow-up CO absorption observations at higher spectral resolution ($R = 5000 \sim 1000$) with *Subaru.* Recently, *Herschel* made extensive observations of highly-excited CO lines in emission in the far-infrared. The two data sets (absorption and emission) sometimes provide us with apparently inconsistent results. One case is starburst galaxies: *Subaru* observations showed low temperature of molecular gas toward the starburst NGC 253, while *Herschel* detected highly excited CO lines in the starburst. This suggests that warm molecular clouds are more deeply embedded than newly formed star clusters. The other case is obscured AGNs; *Herschel* detected highly excited CO lines in emission in nearby AGNs, while *AKARI* and *Subaru* observations showed CO absorption only in some of the obscured AGNs. This could reflect the difference of nature of molecular tori in these AGNs. We propose the combination of the absorption and emission observations as an effective tool to reveal geometry of warm molecular clouds in active galaxies.

Key words: Galaxies: active — Galaxies: nuclei — ISM: lines and bands — ISM: molecules

1. INTRODUCTION

Many lines of evidence suggest that much of the variety in AGNs types is not due to the intrinsic difference but is attributed to varying orientation of central regions with strongly non-spherical geometry relative to the line of sight. In this scenario ("unified model" of AGNs), the molecular tori are the key components. However, we have only a crude idea of the physical structure and characteristics of the tori, and it has been long-awaited to observe the tori directly and to reveal their physical nature.

In this paper, we discuss observations of highly excited CO lines both in absorption and in emission. The combination of the two types of observations is expected to race physical properties of hot molecular clouds in AGNs.

We apply this technique also to starburst galaxies to reveal the relation between stellar clusters and hot molecular clouds in the galaxies.

2. OBSERVATIONS

We employed absorption observations of molecular CO lines toward starbursts and obscured AGNs against bright infrared continua. We focused observations of CO P- and R-branches of fundamental vibration-rotation band at 4.7 μm because many lines over a wide range of energies at various J levels could be observed simultaneously there, which enabled us to determine temperatures and column densities very accurately.

We made two types of absorption observations. One was low-resolution survey observations with *AKARI* and the other was high-resolution follow-up observations with *Subaru.*

AKARI-IRC, with its superb sensitivity, observed

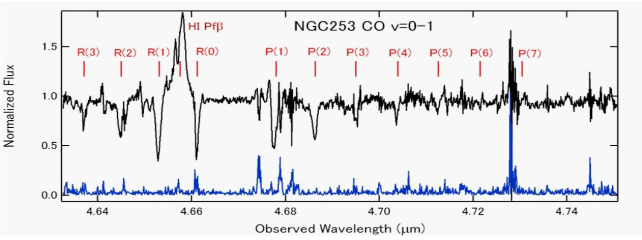

Figure 1. CO absorption spectrum observed with *Subaru* toward the starburst NGC 253. The upper line shows the normalized spectrum, and the lower line shows relative errors.

many obscured AGNs in the near-infrared, without the effect of terrestrial atmosphere. This is an ideal data set for the study of starbursts and obscured AGN. We used *AKARI* prism (NP) and grism (NG) modes, which had spectral resolution of $R \sim 19$ at 3.5 μm and $R \sim 120$ at 3.6 μm respectively. Although the spectral resolution of *AKARI* was not good enough to resolve each rotational-transition line, we could derive temperature and column density of gas by model-fitting.

We observed selected targets with *Subaru*-IRCS. Typical spectral resolution was $R = 5000 \sim 10000$ depending on the slit width. See Shirahata et al. (2013) for more details. The most important point of the *Subaru* observations was that each rotational-transition line could be resolved so that physical properties could be estimated reliably, although the observable spectral range was pretty much limited due to the effect of terrestrial atmosphere.

3. RESULTS AND DISCUSSIONS

3.1. Starbursts

Figure 1 shows absorption spectra of CO lines observed with *Subaru* toward the center of the starburst galaxy NGC 253. Each rotational transition is clearly seen with narrow line width and with the distribution concentrated in lower-J transitions ($J < 4$). This indicates that the molecular gas observed in absorption toward NGC 253 has relatively low temperature ($T \sim 30$ K).

On the other hand, *Herschel* detected high-J CO lines in emission in NGC 253 (Mashian et al., 2015) with J up to 18, which indicates the existence of hot molecular gas ($T \gg 100$ K).

We attribute this apparent discrepancy of the two data sets to the difference of distribution of molecular gas between the hot component and the cold one. We made absorption observations toward the brightest continuum source, a stellar cluster, in the K band. Our non-detection of hot molecular gas in absorption means that only the cold component exists in front of the cluster along the line of sight and the hot molecular component should reside behind the stellar cluster. Hence we conclude that most of the starburst activity (traced by hot molecular clouds) are heavily obscured even in the near-infrared and only the surface of the activities can be seen as the stellar cluster in the near infrared.

3.2. Obscured AGNs

- Observational Results

Herschel detected high-J CO lines in many obscured AGNs, which clearly indicated the existence of hot molecular clouds in these sources (e.g., Mashian et al. 2015). However only some fraction of the obscured AGNs showed CO in absorption.

AKARI detected CO absorption feature toward many obscured AGNs. They showed broad absorption features, which clearly indicated that the gas responsible for absorption had high temperature ($T \gg 100$ K).

We made follow-up observations with *Subaru* toward obscured AGNs observed with *AKARI*. The most representative example is IRAS 08572+3915 (Shirahata et al., 2013). Figure 2 shows high-J CO lines, up to $J = 17$, in absorption. The result indicated the existence of hot molecular clouds ($T \sim 300$ K).

On the other hand, not all the obscured AGNs showed the CO absorption feature. The most notable example is Mrk 231; neither *AKARI* nor *Subaru* detected any hint of CO absorption toward the source. It was also the case for the archetypal Seyfert-2 NGC 1068 (see also Lutz et al. 2004).

- Continuum Source

To have molecular lines in absorption, bright continuum source is required at 4.7 μm. One possibility is the central engine itself as the continuum source. However, the inferred column density of Hydrogen is much smaller than those observed in the X-ray, which is thought to reach the central engines. Hence it is highly improbable to have the central engine as the continuum source.

Another possibility is the thermal emission of dust at the inner wall of the molecular tori illuminated by the central engine. In this case, the temperature of dust is thought to be close the the sublimation temperature of dust. Then strong thermal radiation is expected at 4.7 μm. Hence

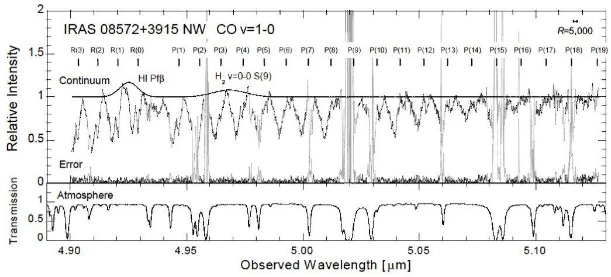

Figure 2. CO absorption spectrum observed with *Subaru* toward the obscured AGN IRAS 08572+3915 (Shirahata et al., 2013). The upper panel shows the normalized spectrum, and the lower panel shows the atmospheric transmission.

we conclude that the thermal emission by hot dust illuminated by the central engine as the most promising continuum source.

- Hot Molecular Clouds

The most notable question is what makes the difference between the AGNs with the CO absorption and those without the absorption. Both of them have the hot molecular component as indicated by *Herschel* observations.

One possibility is that the molecular gas in the sources without the CO absorption is so dusty that molecular clouds themselves could be optically thick with dust in the mid-infrared. Another possibility is a geometrical effect; if molecular tori have a complicated structure, then we could have a line of sight along which we see only the dust layer illuminated by the central engine without intervening molecular clouds on the way.

As shown above, the combination of CO observations of emission with those of absorption is an effective tool to reveal new insights in the centers of active galaxies.

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