Study on the Interstellar OH Radical in Mid-Infrared

Young Chol Minh[1] and Yong Sun Park[2]

[1] *Korea Astronomy and Space Science Institute, Korea*
[2] *Seoul National University, Korea*

ABSTRACT

The powerful spectroscopic capability of *SPICA* in mid- and far-infrared bands will certainly open a totally new window to understand the universe through chemical diversity. Huge amount of molecular lines can be detected in this wavelength, but most of them have never been studied before although they must contain abundant very new information on the interstellar conditions. The OH radical is one of the key molecules to be observed in the interstellar space related to shock process, which also forms H_2O, SiO, and other major molecular species. Except OH maser emissions at around 1.7 GHz, its thermal emission has not been studied much because its transition wavelengths are mostly in mid- and far-infrared. The OH fractional abundance relative to H_2 is expected be enhanced more than two orders of magnitudes behind the shock but it is also detected in cool, extended clouds. Observations of the OH transitions in *SPICA*'s wavelengths towards various Galactic and extragalactic astronomical sources will certainly provide exciting new results, especially in relation to prevalent shock related phenomena.

1. *SPICA* AND SENSITIVE SPECTROSCOPIC OBSERVATIONS

The Japanese-led mission *SPICA* is the next-generation, space infrared observatory which will be consisted of a 3.2-meter cryogenically cooled (6 K) telescope and state-of-the art detectors (Nakagawa et al. 2011). Under this extremely low background level environment, *SPICA* will provide high spatial resolution and unprecedented sensitivity in the mid- and far-infrared. Its powerful spectroscopic capability in this wavelength, which is expected to be more than an order of magnitude better in sensitivity compared to PACS of *Herschel* (Pilbratt et al. 2010), will certainly open a totally new window to understand the universe through chemical diversity.

In the mid- and far-infrared bands, there exist various molecular transitions from vibrational states (mostly resulted from the stretching or bending modes), rotational-vibrational states, and high-energy rotational states. Compared to the electronic and rotational states of molecular lines, these infrared transitions have not been studied much not only for the relatively weak lines, but also for the *major* transitions. Figure 1 shows a sample of the spectral line survey obtained with *ISO* (Kessler et al. 1996) toward an asymptotic giant branch star, CRL 618, evolving toward the planetary nebula stage (Herpin & Cernicharo 2000). This figure clearly shows the importance of the infrared transitions from the *major* molecules to understand the physical properties of astronomical objects. The hydroxyl radical (OH) is one of those *major* molecules which needs to be studied much further considering its importance in the interstellar processes.

In addition, high sensitivity spectroscopic studies in the *SPICA*'s mid- and far-infrared bands will certainly reveal enormous number of weak lines. Most of these lines have never been studied before, but they must contain huge amount of unexpected important information which may change our fundamental view of the universe. This article is to stress the importance of the sensitive spectroscopic observations in the *SPICA*'s band.

2. OH RADICAL

OH is one of the first radicals detected in the diffuse gas clouds. Radicals contain at least one unpaired electron which often make them highly reactive and unstable. Free radicals are too short-lived to be observed in the terrestrial environment, but many of them are now observed in space as important tracers of interstellar processes (Kwok 2007).

The energy diagram for the OH molecule is shown in Figure 2 (Wampfler et al. 2013). The + and − notations refer to the total parity of the Λ doublets. Due to an unpaired electron ($S = 1/2$) and the magnetic moment of the nuclei the levels further split into two hyperfine states. The ground state of OH is $^2\Pi_{3/2,1/2}$, which emits four maser lines at around 1.7 GHz (two main lines: 1665 & 1667 MHz and two satellite lines: 1612 & 1720 MHz). These OH maser lines have been studied towards many star-forming regions as important tracers of the shocked gas.

Except these maser lines, however, other important transitions from OH have wavelengths mostly in the infrared bands which hinders easy access in the ground. Although some of the OH infrared transitions have been observed previously with space telescopes, such as *KAO*, *ISO*, *Herschel*, or *SOFIA*, studies for OH are still very limited compared to its importance in the space.

We have tested the OH excitation using an LVG-like code of van der Tak et al. (2007). Excitation of OH is mainly controlled by either collisions or radiative pumping, but not by both, and a part of the results is shown in Figure 3. As indicated in the panel, $T_{\rm kin}$ = 100 and 200 K, and $n_{\rm H_2} = 10^4$ and 10^5 cm^{-3} have been assumed. These results are the cases

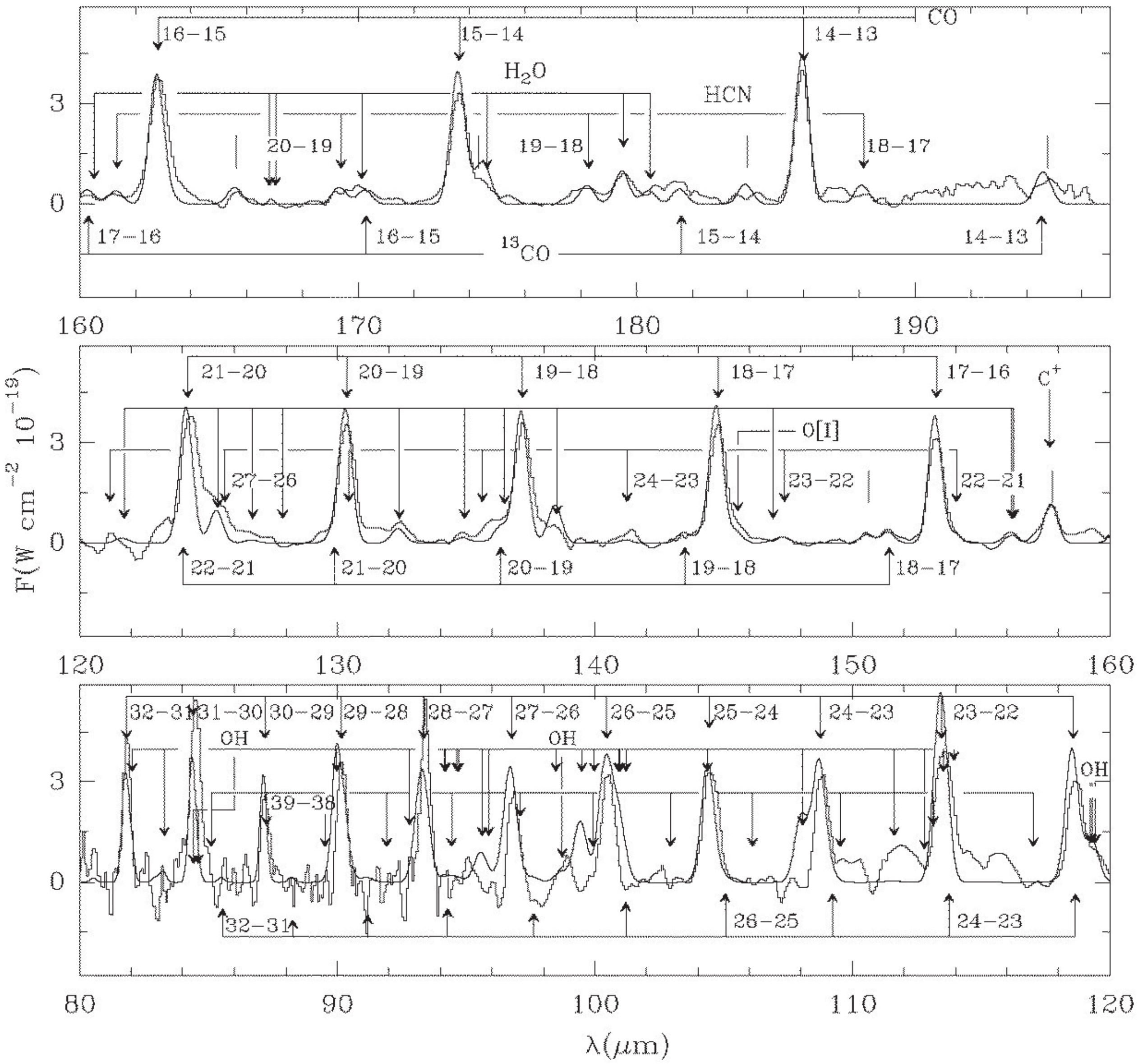

Figure 1. Continuum-subtracted spectra of CRL 618 (long-wavelength detectors of *ISO*). The plot indicates a Gaussian fit to this feature (Figure 1 of Herpin & Cernicharo 2000).

of the total OH column density of $1.0 \times 10^{18}\,\mathrm{cm}^{-2}$ with a linewidth of $5\,\mathrm{km\,s}^{-1}$. We are preparing an elaborate model for the OH excitation for some of its transitions to be used as meaningful tracers of interstellar conditions (Park et al., in preparation).

Shock is everywhere in space. Almost all objects in the space are associated with shock, such as supernova remnants (SNRs), expanding hot gas, HII regions, circumstellar envelopes, (proto-)planetary nebulae, star formation regions, etc. Among interstellar molecules, OH, H_2O, and SiO are thought to be good shock tracers, as they are also observed as masers. OH is a key molecule in the formation of these species.

In dense quiet gas phase, where ion-molecule reactions dominate, OH usually forms by the hydrogen abstraction sequence followed by the dissociative recombination of H_3O^+ (Jensen et al. 2000). This results in the fractional abundance of OH, $f_{\mathrm{OH}} \approx 10^{-8}$, relative to total H_2, in the density of $n_{\mathrm{H}_2} = 10^4 - 10^6\,\mathrm{cm}^{-3}$. Elevated kinetic temperature in the shocked region, however, enables the endothermic reactions to be processed which were inactive in the quiet gas region, and enhances f_{OH} to be more than 2 orders of magnitudes ($\geq 10^{-6}$).

At T_{kin} above $\sim$ 300 K, important production reactions of OH, H_2O, and SiO become $\mathrm{O} + \mathrm{H}_2 \rightarrow \mathrm{OH} + \mathrm{H}$, $\mathrm{OH} + \mathrm{H}_2 \rightarrow \mathrm{H}_2\mathrm{O} + \mathrm{H}$, and $\mathrm{Si} + \mathrm{OH} \rightarrow \mathrm{SiO} + \mathrm{H}$ (Neufeld & Dalgarno 1989; Pineau des Forets & Flower 1996). Immediately behind a shock, H_2O is formed fast and contains most of the oxygen, but it is more easily dissociated than OH by photons, and quickly depleted to the grain surface in denser regions. SiO is an unambiguous shock tracer, since Si is highly depleted in the quiet phase (by larger than 1000) and needs to be sputtered or desorbed from grain mantles, or

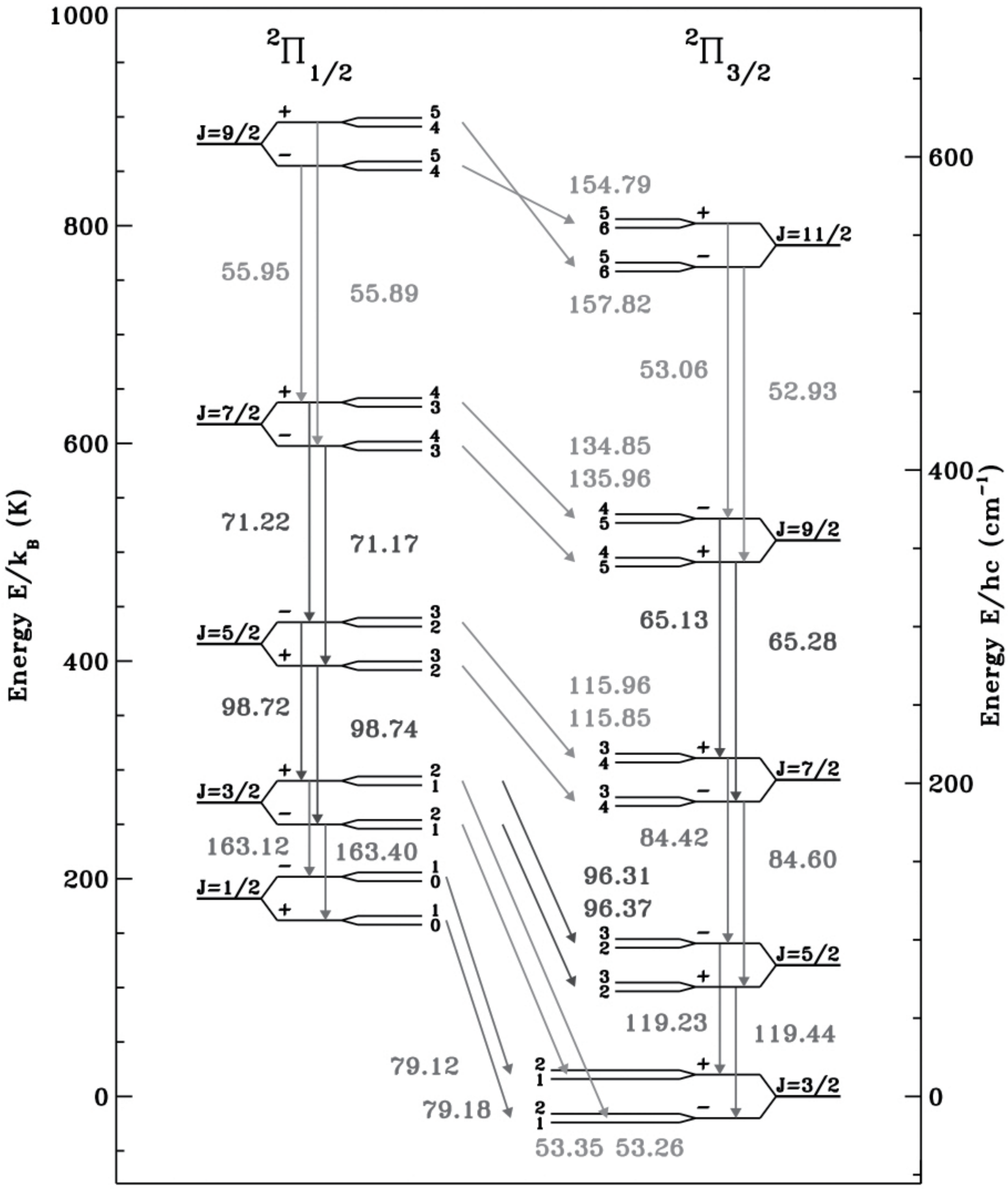

Figure 2. OH transitions. Wavelengths are given in units of microns (Figure 1 of Wampfler et al. 2013).

destructed to be in the gas phase (Pineau des Forets & Flower 1996). OH is playing a key role in relation to the formation of these molecules, and among three molecules, OH is the only one also detected in cool, extended clouds.

In shock and PDRs, abundances are clearly enhanced mainly by the activation of endothermic neutral-neutral reactions. But there are significant difficulties to interpret these regions using these shock tracers. It is not only because of different predictions by different models, but also because emission from these regions are resulted from the mixed effects caused by different physical conditions, chemical variations, or radiative transfer. We definitely need to have more data to understand these sources, especially in the mid- and far-infrared region, since many of the molecular lines emitted from shock regions lie in this wavelength.

3. OUR GALACTIC CENTER

Interstellar molecular lines observed in the mid- and far-infrared region will provide important information to understand the properties of various Galactic and extragalactic sources. Chemical information of the observed lines are essential to understand physical conditions of, for example, complicated massive star-forming regions, embedded deeply inside

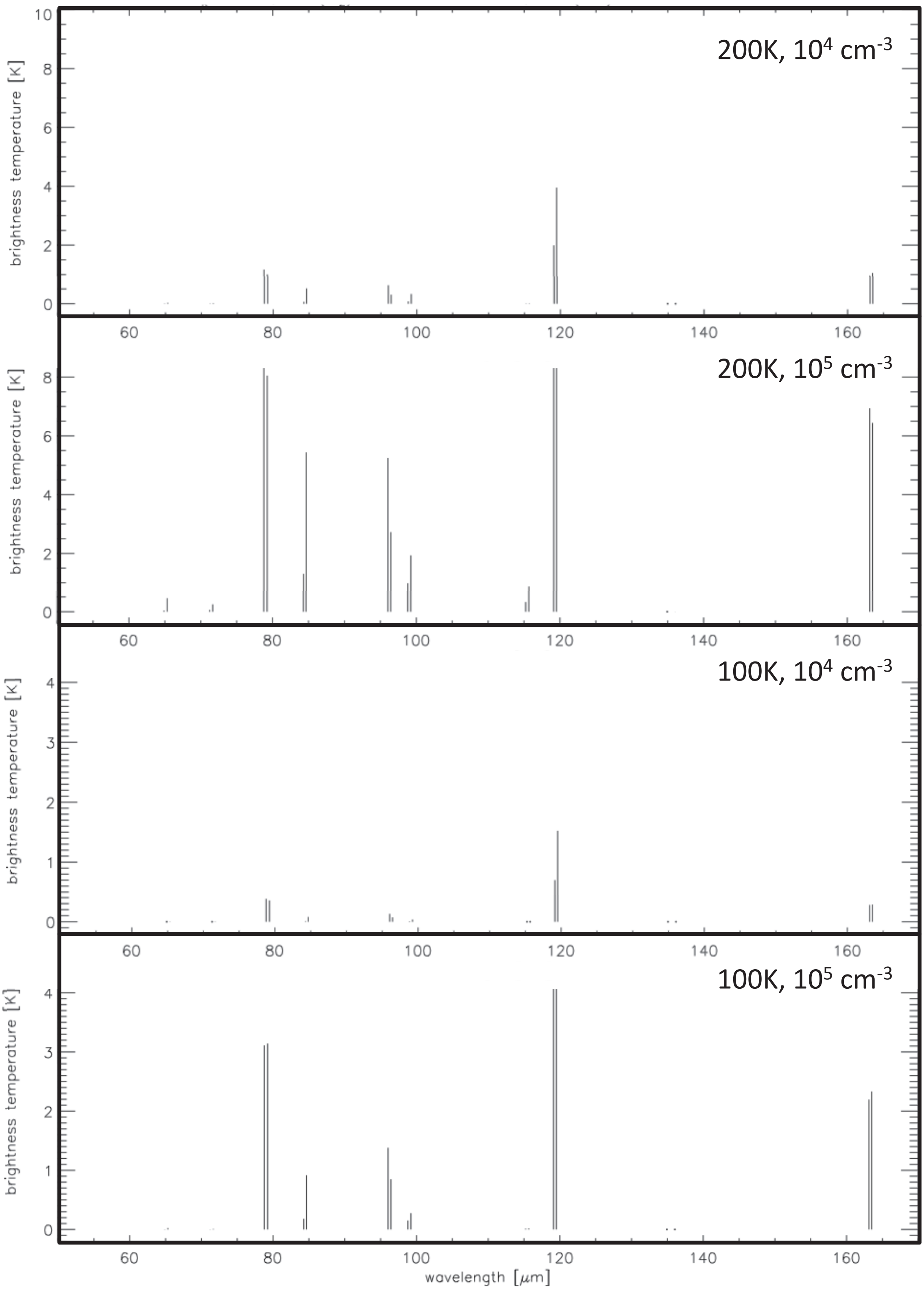

Figure 3. Sample results of the OH excitation model calculated by using the modified code of van der Tak et al. (2007).

dense GMCs (e.g., Minh et al. 2010, 2011), since there are not many probes available to investigate these regions. Here we introduce our Galactic center, as a candidate for the study of shock features with OH and/or other shock tracers, which will provide important clues to understand this extremely complicated region. Especially we do not have many evidences indicating apparent interactions among various different components which are crucial to understand the nature and evolution of this region.

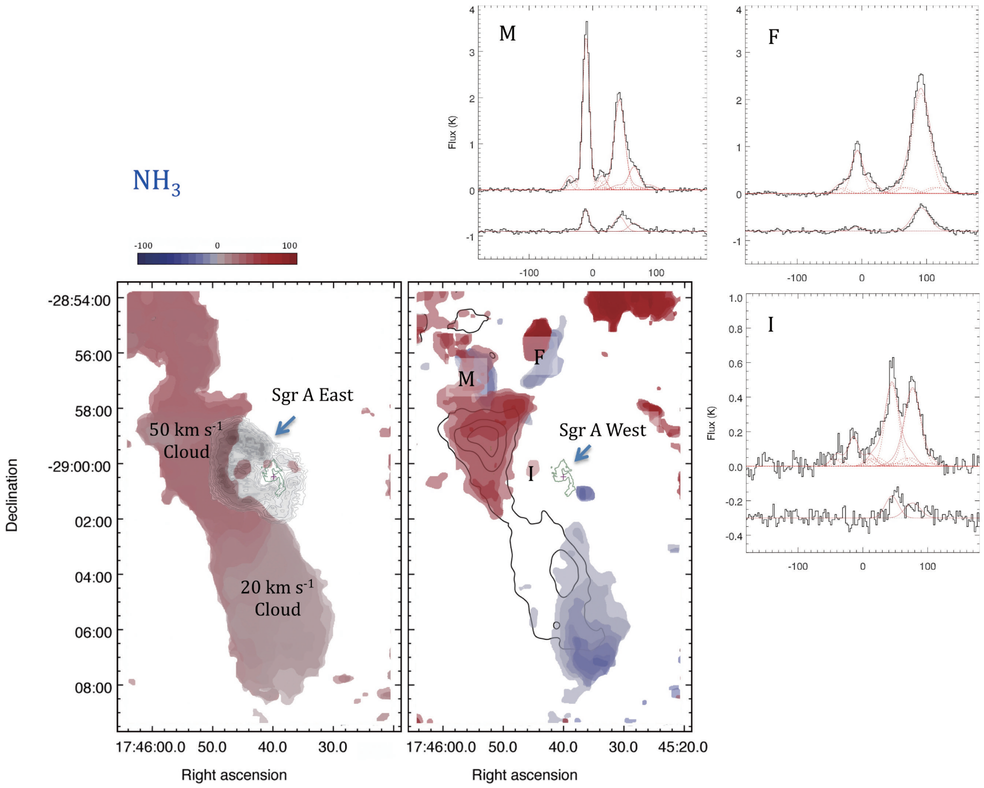

Figure 4. NH$_3$ (6, 6) observational results made with Green Bank Telescope. Two panels in the bottom-left are color-coded channel maps for main gas condensations, the 50 km s^{-1} and the 20 km s^{-1} clouds (*left*) and newly found streaming gas components (*right*). The velocity scale is shown as a color bar on top of these panels. Spectra obtained towards the position, F, M, and I are shown in the upper-right side. Gaussian fit results are overlapped with the observed spectra. See details of this figure in Minh et al. (2013).

Neutral gas near the Galactic center is predominantly molecular. Most of the gas within ~20 pc (in projection) from Sgr A* is concentrated into two massive clouds, called M−0.02 – 0.07 (also referred to as the "50 km s^{-1} cloud") and M−0.13 – 0.8 (the "20 km s^{-1} cloud") according to their galactic coordinates (Guesten et al. 1981). These two clouds have comparable masses ($\sim 5 \times 10^5$ M$_\odot$) and linear dimensions (~ 10–15 pc), and they have a complicated morphological structure (e.g., Guesten et al. 1981; Armstrong & Barrett 1985). The large linewidths of the observed transitions indicate the existence of a high degree of turbulence. Subsequent to early absorption line observations of OH and H$_2$CO, spectral lines and dust emissions from these clouds have been studied extensively (e.g., Snyder et al. 1969; Guesten et al. 1981; Minh et al. 1992), and it has been found that the physical and chemical properties of these molecular clouds differ substantially from those in the galactic disk.

This molecular gas has been thought to interact with the central components in the inner 10 pc of our Galactic Center, such as the circumnuclear disk (CND) or the SNR Sgr A East (e.g., Ho et al. 1991; Coil & Ho 1999). The CND is a ring-like, dense ($\geq 10^5$ cm^{-3}), highly turbulent ($\Delta v \geq 40$ km s^{-1}), and clumpy molecular gas, which surrounds Sgr A* with an inner edge at ~1.5 pc and an outer edge at ~ 3 – 4 pc (e.g., Liu et al. 2013, and references therein). Sgr A East is an expanding shell of a synchrotron emission that lies behind Sgr A*; it is thought to interact with the CND and also with the ambient 50 km s^{-1} cloud. Sgr A East appears to be pushing the gas away from its nucleus, forming ridges of material on all sides; however, some material, such as the NH$_3$ filamentary streamers, may also move toward the nucleus and possibly feed the nucleus.

As shown in Figure 4, we recently found that there exist various streaming components associated with the CND near our Galactic center which are apparently located out of the galactic plane and have highly eccentric orbits (Minh et al. 2013). Some of these streaming components are expected to be sources that feed the CND of our Galactic center directly and episodically. However, the structure and evolution of these components have not yet known well which may provide a crucial clue to understand the infall of gas to Sgr A*, the supermassive black hole (SMBH, mass $\sim 2 \times 10^6$ $M_\odot$; Reid et al. 1999; Ghez et al. 2005), and the formation of highly eccentric young stellar clusters located very near to SMBH.

This study could be extended toward the northeast region outside Figure 4, where a number of unusual non-thermal filaments (NTFs), referred to as streaks, threads, and filaments, have been found (e.g., Yusef-Zadeh et al. 1984; Lang et al. 1999). These features have lengths of tens of parsecs, yet widths of only less than 0.5 pc, orientation roughly perpendicular to the Galactic plane. Studies on the association between NTFs and both ionized and molecular gas components will provide an important clue to understand the nature of NTFs. We expect that emissions from OH or other shock tracers, especially in infrared, will certainly provide fundamental information to understand this important but complicated region.

4. SUMMARY

The next-generation, space infrared observatory, *SPICA*, is going to have a powerful spectroscopic capability in mid- and far-infrared bands. We expect that huge amount of molecular lines will be detected in this wavelength, which will certainly open a totally new window to understand the universe through chemical diversity. A considerable amount of the detected lines has never been studied before, but must contain abundant very new information on the interstellar conditions. This article is just to stress the importance of spectroscopic measurements in mid- and far-infrared bands, and the OH radical is introduced as an example of the important species to be studied. OH is one of the key molecules to be observed in the interstellar space related to shock process, which also forms H_2O, SiO, and other major molecular species. The OH fractional abundance relative to H_2 is expected be enhanced more than two orders of magnitudes behind the shock but it is also detected in cool, extended clouds. Except OH maser emissions at around 1.7 GHz, however, its thermal emission has not been studied much because its transition wavelengths are mostly in mid- and far-infrared. We test the OH excitation model to be used as a tool to trace the specific physical conditions. Observations of the OH transitions in *SPICA*'s wavelengths towards various Galactic and extragalactic astronomical sources will certainly provide exciting new results, especially in relation to prevalent shock related phenomena. Here we introduced our Galactic center as a possible candidate source for the study of this kind.

REFERENCES

Armstrong, J. T., & Barrett, A. H. 1985, ApJS, 57, 535
Coil, A. L., & Ho, P. T. P. 1999, ApJ, 513, 752
Ghez, A. M., et al. 2005, ApJ, 620, 744
Guesten, R., et al. 1981, A&A, 103, 197
Herpin, F., & Cernicharo, J. 2000, ApJ, 530, L129
Ho, P. T. P., et al. 1991, Nature, 350, 309
Jensen, M. J., et al. 2000, ApJ, 543, 764
Kessler, M. F., et al. 1996, A&A, 315, L27
Kwok, S. 2007, Physics and Chemistry of the Interstellar Medium (Sausalito, California: University Science Books), 1st ed.
Lang, C. C., et al. 1999, ApJ, 521, L41
Liu, H. B., et al. 2013, ApJ, 770, 44
Minh, Y. C., et al. 1992, A&A, 258, 489
— 2010, ApJ, 723, 1231
— 2011, ApJ, 737, L25
— 2013, ApJ, 773, 31
Nakagawa, T., Matsuhara, H., & Kawakatsu, Y. 2011, in Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave (SPIE), vol. 8442 of SPIE, 84420O
Neufeld, D. A., & Dalgarno, A. 1989, ApJ, 340, 869
Pilbratt, G. L., et al. 2010, A&A, 518, L2
Pineau des Forets, G., & Flower, D. 1996, in Molecules in astrophysics: probes & processes, edited by E. F. van Dishoeck (Dordrecht: Kluwer), vol. 178 of IAU Symp., 113
Reid, M. J., et al. 1999, ApJ, 524, 816
Snyder, L. E., et al. 1969, BAAS, 1, 363
van der Tak, F. F. S., et al. 2007, A&A, 468, 627
Wampfler, S. F., et al. 2013, A&A, 552, 56
Yusef-Zadeh, F., et al. 1984, Nature, 310, 557