DETECTION OF PARENT H₂O AND CO₂ MOLECULES IN THE 2.5–5 μm SPECTRUM OF COMET C/2007 N3 (LULIN) OBSERVED WITH AKARI

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ABSTRACT

Comet C/2007 N3 (Lulin) was observed with the Japanese infrared satellite AKARI in the near-infrared at a post-perihelion heliocentric distance of 1.7 AU. Observations were performed with the spectroscopic (2.5–5.0 μm) and imaging (2.4, 3.2, and 4.1 μm) modes on 2009 March 30 and 31 UT, respectively. AKARI images of the comet exhibit a sunward crescent-like shape coma and a dust tail extended toward the anti-solar direction. The 4.1 μm image (CO/CO₂ and dust grains) shows a distribution different from the 2.4 and 3.2 μm images (H₂O and dust grains). The observed spectrum shows distinct bands at 2.66 and 4.26 μm, attributed to H₂O and CO₂, respectively. This is the fifth comet in which CO₂ has been directly detected in the near-infrared spectrum. In addition, CO at 4.67 μm and a broad 3.2–3.6 μm emission band from C–H bearing molecules were detected in the AKARI spectrum. The relative abundance ratios CO₂/H₂O and CO/H₂O derived from the molecular production rates are ~4%–5% and <2%, respectively. Comet Lulin belongs to the group that has relatively low abundances of CO and CO₂ among all observed comets.

Key words: comets: general – comets: individual (C/2007 N3 Lulin) – protoplanetary disks – Oort Cloud

1. INTRODUCTION

Since comets are remnants from the protoplanetary disk and the least processed bodies in the solar system, their composition and heterogeneity and their relation to their dynamical history help our understanding of the formation process of planetesimals and planets in the early solar nebula. One of the main goals of cometary studies is the determination of the composition of volatile species contained in the nucleus as ice. Besides water (H₂O), carbon monoxide (CO), carbon dioxide (CO₂), and methanol (CH₃OH) are the most abundant species in comet nuclei. They are the key species that provide information on the formation and evolution mechanisms and on the materials from which they originate. Most parent molecules, which sublimate directly from the nucleus, have strong fundamental bands of vibration in the near-IR (2.5–5 μm). H₂O and CO₂ have the fundamental v₁ band at 2.66 and 4.26 μm, respectively. CO has the v₁(1–0) band at 4.67 μm. Although the near-IR region is partly accessible from the ground and advances in modern spectrometers with high spectral resolving powers have made a great progress in the study of H₂O hot bands and organic molecules (Disanti & Mumma 2008; references therein), the most abundant parent molecules (especially CO₂) are difficult to observe directly from the ground because they are also present in the terrestrial atmosphere and strong telluric absorption bands make the atmosphere completely opaque. Symmetric molecules, such as CO₂, do not have a permanent electric dipole moment and thus cannot be observed even in the radio range from the ground.

The advent of space missions allows us to study the emission from cometary volatiles in the entire 2.5–5 μm region. Parent CO₂ from the comet nucleus was detected in the coma of comet 1P/Halley by the Russian Vega space probe for the first time (Combes et al. 1988). Since then, it has been directly observed in only three other comets: Hale-Bopp (Crovisier et al. 1996, 1997, 1999a) and 103P/Hartley (Colangeli et al. 1999; Crovisier et al. 1999b) with Infrared Space Observatory (ISO), and 9P/Tempe1 with the Deep Impact flyby spacecraft (A’Hearn et al. 2005; Feaga et al. 2007).

With regard to imaging observations, Spitzer Space Telescope also observes the cometary CO and CO₂ in the near-IR with the Infrared Array Camera (IRAC). Recent studies report the CO₂ production rates of comets 21P/Giacobini–Zinner and 73P/Schwassmann–Wachmann (Pittichová et al. 2008; Reach et al. 2009). The IRAC 4.5 μm image is, however, a combination of CO, CO₂, and dust thermal emission. It is difficult to derive the CO and CO₂ production rates separately.
AKARI, the Japanese IR satellite (Murakami et al. 2007), provides a near-IR spectroscopic capability from the space for the first time after ISO. We present here the results of a search for parent molecules in comet C/2007 N3 (Lulin), hereafter called C/Lulin, observed with AKARI at near-IR wavelengths. C/Lulin is one of the Oort cloud comets, which was discovered by Lulin Observatory (Taiwan) on 2007 July 11. The comet passed the perihelion on 2009 January 10.6 UT with the heliocentric distance of 1.36 AU and a geocentric distance of 0.41 AU.

2. OBSERVATIONS AND DATA REDUCTION

AKARI is equipped with a 68.5 cm cooled telescope and two scientific instruments, the Far-Infrared Surveyor (FIS; Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007). AKARI was launched on 2006 February 21 UT, and its liquid helium (LHe) cryogen boiled off on 2007 August 26 UT, 550 days after launch. In the post-helium phase (Phase 3), the telescope and scientific instruments are kept around 40 K by a mechanical cooler and only near-IR observations (1.8–5.5 μm) are carried out. Near-IR observations, both imaging and spectroscopy, of C/Lulin were performed with AKARI/IRC during this post-helium phase as part of the Director’s Time observations. We have only several chances to observe this comet because AKARI has the visibility restriction of its solar elongation angle within 90 ± 1 deg. At the time of the observation, the comet was at a heliocentric distance of 1.70 AU and a geocentric distance of 1.36–1.37 AU.

Spectroscopic observations were carried out on 2009 March 30 at 15:53 UT. The IRCZ4 AKARI IRC observing template (AOTZ4) was used. The near-IR grism (NG) mode of IRCZ4 uses a near-IR grism (2.5–5 μm), in which a target is located on the small 1 ′ × 1 ′ aperture (Np) for point-source grism spectroscopy. The effective spectral resolution is R ∼ 100 at 3.6 μm for a point source in Phase 3. The spectral resolution is expected to be lower than this value for extended sources such as comets. Raw data were processed through the IRC Spectroscopy Toolkit for Phase 3 data (version 20090211) with the new spectral responsivity (version 20091113).10 A one-dimensional spectrum of the C/Lulin was extracted with a pseudo aperture of 60 ″ × 4.5 ″ at 4.5 ″ west from the comet nucleus (see Figure 1). Unfortunately, the east side coma to the nucleus is affected by the contamination of a background field star. We select this pseudo aperture position in order to avoid the opacity effect in the source (see below). The corresponding aperture position for the spectrum extraction is depicted in Figure 1.

Imaging observations with AOTZ3 were performed on 2009 March 31 at 00:07 UT, which was 8 hr after the spectroscopic observations, yielding images of 1.9–2.8 (N2 band), 2.7–3.8 (N3), and 3.6–5.3 (N4) μm for at least two different positions. The reference wavelengths of N2, N3, and N4 bands are 2.4, 3.2, and 4.1 μm, respectively. The data were processed with the IRC Imaging Toolkit for Phase 3 data (version 20081015). The resultant IRC image has a pixel size of 1′46 and the FWHM of the image size is ~ 4″7 in Phase 3 (Onaka et al. 2008), corresponding to 1440 km and 4630 km at the geocentric distance of 1.36 AU, respectively.

The observation parameters are summarized in Table 1. The temperature of the telescope system and the IRC during Phase 3 is above 40 K and is gradually increasing. Note that we need further careful calibration and analysis with regard to the absolute flux calibration and weak spectral features, although any remarkable systematic changes in the sensitivity are not seen in Phase 3 at the moment. Please refer to AKARI IRC Data User Manual for Post-Helium (Phase 3) Mission10 for more detail of the calibration in Phase 3. The performance in the LHe cryogen phase is described in IRC instrument papers (Onaka et al. 2007; Ida et al. 2007; Ohshima et al. 2007).

3. RESULTS AND DISCUSSION

Figure 1 shows a RGB false color image of C/Lulin produced from the AKARI/IRC N2 (blue: 1.9–2.8 μm), N3 (green: 2.7–3.8 μm), and N4 (red: 3.6–5.3 μm) band data. The images are degraded by a Gaussian beam with the FWHM of 4.5 ″, so that they match with each other in the point-spread function. The AKARI images of comet exhibit a crescent-like shape coma sunward and a dust tail extending toward the anti-solar direction (i.e., eastward). The N4 (red) image (CO/CO2 and dust grains) has a distribution different from those of the N2 (blue) and N3 (green) images (H2O and dust grains). Since both the N2 and N3 filters cover the 2.7–2.8 μm region of H2O emission, the blue and green images resemble each other.

The AKARI spectrum of C/Lulin is characterized by the typical vibrational bands of parent molecules in the coma (Figure 2). Two strong v3 bands of H2O at 2.66 μm and CO2 at 4.26 μm are present in the AKARI spectrum of C/Lulin. In addition, the carbon monoxide v1(0) band at 4.67 μm and a broad 3.2–3.6 μm emission band, which corresponds to a stretching mode of C–H in hydrocarbons, can be seen. We will concentrate on their interpretation based on their derived production rates (outgassing rates) in the following.

To estimate the molecular abundance in the comet nucleus, the flux densities are converted into the molecular production rates. For the accurate measurement of the production rate, opacity effects should be taken into account because it is probable that these parent molecules are optically thick near the nucleus (Combes et al. 1988; Crovisier 2006). Feaga et al. (2007) discussed this opacity effect near the nucleus of 9P/Tempel for H2O and CO2, and derived the critical column density at which opacity effects become non-negligible for two

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10 See AKARI (ASTRO-F) Observers Page (http://www.ir.isas.jaxa.jp/ASTRO-F/Observation/).
The time and spatial variations are beyond the scope of this Letter and will be studied in the forthcoming papers.

The water band around 2.7 μm is a blend of at least two fundamental vibration (ν1 and ν3) bands and hot bands (ν2 + ν3 – ν2 and ν1 + ν3 – ν1), but the ν3 band is expected to have the largest intensity and make the most dominant contribution to this region. The weak OH ν(1–0) resonance also contributes to the shoulder around 2.8 μm (Bockelée-Morvan & Crovisier 1989). We integrated the water band flux in the 2.56–2.83 μm range. The contribution of weak OH ν(1–0) band to the entire band flux is expected to be negligible. We used the value 3.6 × 10^-4 s^-1 as the total H2O g-factor in this region (Bockelée-Morvan & Crovisier 1989). The observed band flux corresponds to a water production rate Q(H2O) = (7.6 ± 0.1) × 10^27 molecules s^-1 (hereafter, the absolute calibration uncertainty is not included in the error).

CO2 cannot be directly observed in the near-IR from the ground because of strong telluric absorption. As described above, CO2 has been directly detected only in four comets thus far. The ν3 band of CO2 at 4.26 μm is clearly detected in our spectrum of C/Lulin. By assuming an expansion velocity of 0.8 km s^-1, we have derived, directly from our integrated band flux, the production rate Q(CO2) = (3.4 ± 0.1) × 10^27 molecules s^-1. The relative production rate of CO2 compared to H2O derived from our observation is 4.5%. The ratio of the CO2 to H2O production rates is greater than 20% for comet Hale-Bopp at 2.9 AU (Crovisier et al. 1997) and ~8%–10% for Hartley 2 at 1.0 AU (Colangeli et al. 1999; Crovisier et al. 1999b), respectively. Comet Hale-Bopp was, however, observed at more than 2.9 AU far from the Sun. Its high ratio (>20%) is likely due to the high volatility of CO2 compared to H2O. Using Q(CO2)/Q(H2O) of ~0.3 obtained at 2.9 AU, the ratio at 1 AU can be extrapolated as ~6% (Bockelée-Morvan et al. 2004). In the case of comet 9P/Tempel at 1.5 AU, it is reported that the CO2-to-H2O ratio is ~7% (Feaga et al. 2007). Each study, however, adopted different values for the g-factor of water. In Colangeli et al. (1999) and Feaga et al. (2007), they considered a main contribution of ν3 band alone and used the g-factor of 2.6 × 10^-4 and 2.85 × 10^-4 for H2O, respectively. If the same value 3.6 × 10^-4 as this Letter is adopted for water, we obtained [CO2/H2O] ~ 11% for 103P and ~9% for 9P. As for comet 73P, it is suggested that Q(CO2)/Q(H2O) ~ 5%–10% by Spitzer imaging observations (Reach et al. 2009). C/Lulin has a relative CO2 abundance lower than Jupiter-family comets.

The first clear detection of the near-IR ν(1–0) band of CO around 4.7 μm was made at observations of Comet Hyakutake (Mumma et al. 1996; DiSanti et al. 2003). The CO band in near-IR has been detected for eight Oort cloud comets and two Jupiter-family comets with high-dispersion spectrometers from the ground (Bockelée-Morvan et al. 2004; Disanti & Mumma 2008). For Oort cloud comets observed with IR ground-based spectroscopy, the total CO abundance ranged from 1% to 24% relative to H2O (Mumma et al. 2003). Carbon monoxide can be produced in the cometary coma from other precursors, and it can then exhibit both native (direct from the comet nucleus)
Table 2
Molecular Bands Observed in C/2007 N3 (Lulin) with AKARI/IRC

| Molecule | Band | \( \lambda \) (\( \mu \)m) | \( g^a \) (s\(^{-1}\)) | \( \lambda \) (\( \mu \)m) | Flux (W m\(^{-2}\)) | \( Q^b \) (s\(^{-1}\)) |
|----------|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| H\(_2\)O | \( v_3 \) | 3.66 | 0.08 \times 10\(^{-4}\) | 2.56 \(-\) 2.83 | (4.42 \(\pm\) 0.03) \times 10\(^{-15}\) | (7.6 \(\pm\) 0.1) \times 10\(^{28}\) |
|         | \( v_1 \) | 3.73 | 0.5 \times 10\(^{-4}\) |                  |                  |                  |
|         | \( v_2 + v_3 \) | 3.66 | 0.8 \times 10\(^{-4}\) |                  |                  |                  |
|         | \( v_1 + v_3 - v_1 \) | 3.73 | 2.2 \times 10\(^{-4}\) |                  |                  |                  |
| CO\(_2\) | \( v_3 \) | 4.26 | 2.9 \times 10\(^{-4}\) | 4.1 \(-\) 4.4 | (1.23 \(\pm\) 0.02) \times 10\(^{-15}\) | (3.4 \(\pm\) 0.1) \times 10\(^{27}\) |
| CO      | \( v(1-0) \) | 4.67 | 2.6 \times 10\(^{-4}\) | 4.64 \(-\) 4.72 | <4.0 \times 10\(^{-17}\) | <1.3 \times 10\(^{27}\) |

Notes.

\(^a\) Emission rate assuming resonant fluorescence exited by the Sun at 1 AU.

\(^b\) Wavelength integration range where the fluxes are computed.

\(^c\) Absolute calibration uncertainty is not included in the error.

\(^d\) Production rate assuming a molecule distribution with an expansion velocity of 0.8 km s\(^{-1}\).

and extended (or distributed) sources in comets. Both native and extended sources contribute to this value. It is suggested that the native abundance CO/H\(_2\)O has been found to be 0.4%–17% (Mumma et al. 2003; Disanti & Mumma 2008), while for the two Jupiter-family comets (9P/Tempel and 73P/Schwassmann-Wachmann), CO/H\(_2\)O \~{} 4% and <3%, respectively (Disanti & Mumma 2008). On the other hand, space and in situ missions could not detect this band clearly due to the low spectral resolution except for comet Hale-Bopp by ISO (Crovisier et al. 1999a). In the AKARI spectrum of C/Lulin, a weak (2\(\sigma\)) band can be seen around 4.68 \(\mu\)m (Figure 2). It is most likely that this corresponds to the 4.67 \(\mu\)m CO \(v(1-0)\) band. The comet Halley spectrum by Vega (\( R \approx 85\)) might resolve the P and R branches of CO, although the CO band strength is near the detection limit (Combes et al. 1988). The resolved P and R branches are not expected in the IRC spectrum because of the spectral resolution \~{} 100 (see Figure 7 in Crovisier 1987). Our derived upper limit of the CO production rate is \( Q(CO) < 1.3 \times 10^{27} \) molecules s\(^{-1}\) (3\(\sigma\)), when we integrate the flux in the 4.64–4.72 \(\mu\)m region. Improvements in the calibration will lower the detection limit for faint features. It is secure that the corresponding production rate of CO compared to H\(_2\)O is less than 2%.

The 3.52 \(\mu\)m methanol (CH\(_3\)OH) feature can also be seen upon a broad 3.2–3.6 \(\mu\)m emission band from C–H bearing molecules in the spectrum (Figure 2). These 3.2–3.6 \(\mu\)m features may be attributed to a blend of many rovibrational lines belonging to methanol, organics, and hydrocarbons such as methane (CH\(_4\)) and ethane (C\(_2\)H\(_6\)) (Bockelée-Morvan et al. 1995). Methane, ethane, and methanol have been observed in many comets in the near-IR with the ground-based high-resolution spectroscopy (Disanti & Mumma 2008, and references therein). Further detailed identification of each feature in the AKARI spectrum is difficult at the present calibration stage.

The relative abundances CO\(_2\)/H\(_2\)O and CO/H\(_2\)O derived from our observations are \~{} 4%–5% and \<2%, respectively. The value \( Q(CO)/Q(H_2O) \sim{} 4\%–5\% \) is similar to 1P/Halley (3\%–4\%; Combes et al. 1988) and the estimated value \~{} 6\% of Hale-Bopp at 1 AU (Bockelée-Morvan et al. 2004). The value \( Q(CO)/Q(H_2O) < 2\% \) of C/Lulin belongs to the group that has relatively low \( Q(CO)/Q(H_2O) \) values among the comets observed ever. It is similar to the value 0.9% of Oort comet C/1999 S4 (LINEAR; Mumma et al. 2001). C/Lulin was observed at 1.7 AU of the heliocentric distance after the perihelion passage. Since CO is one of the highly volatile species in comet nuclei, CO might be exhausted from the surface of the comet nucleus and highly depleted at the observation epoch, although such phenomena have not yet been reported. It is more probable that the depletion occurred if the comet nucleus condensed at moderately high nebular temperatures. In the present paradigm, comet formation in the early solar nebula extended over a wide range of the heliocentric distance both for Oort cloud and Jupiter-family comets (Dones et al. 2004; Duncan et al. 2004). This suggests that comets could display diversity in their chemical composition depending on the local temperature and nebular composition where they are formed (Bockelée-Morvan et al. 2004). It is believed that Oort cloud comets were formed in the giant planet region of the early solar nebula, although recent dynamical models suggest that comets now in the Oort cloud were contributed in roughly equal numbers both from giant planet and the Kuiper Belt region (Dones et al. 2004). It is reasonable to infer that C/Lulin has a small fraction of CO and CO\(_2\) in its nucleus because it may originate from the region closer to the Sun among the planetesimal formation sites.

Establishing a chemical taxonomy for comets gives us important insights into the planetesimal formation process in the early solar nebula, and it is important to study the chemical diversity of the parent molecules in many more comet samples. Near-IR observations with AKARI will provide precious data for these parent molecules.

4. CONCLUSIONS

We reported the near-IR spectrum and image of comet C/2007 N3 (Lulin) observed with AKARI/IRC on 2009 March 30 and 31, respectively. Both the fundamental vibrational bands of water (2.66 \(\mu\)m) and carbon dioxide (4.26 \(\mu\)m) are clearly detected in the AKARI spectrum. In addition, 3.2–3.6 \(\mu\m\) C–H bearing molecule feature and \( v(1-0) \) band of carbon monoxide (4.67 \(\mu\m\)) are also detected. The relative abundances CO\(_2\)/H\(_2\)O and CO/H\(_2\)O derived from our observations are \~{} 4%–5% and \<2%, respectively. Comet Lulin belongs to the group that has relatively low abundance of CO and CO\(_2\) among all observed comets.

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