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AKARI NEAR-INFRARED SPECTROSCOPIC SURVEY FOR COMETARY VOLATILES

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ABSTRACT

We performed a spectroscopic survey for cometary volatiles with the Infrared Camera onboard the Japanese infrared satellite AKARI. The observations were carried out in the near-infrared wavelength range in the period from 2008 June to 2010 January. In this paper, we summarize the observations and results of the AKARI survey for the mixing ratios of major volatiles in comets. We derived the 2.5–5 μm spectra of 18 comets including both Oort cloud comets and Jupiter-family comets. Prominent emission bands in the observed spectra are the fundamental vibrational bands of water (H_2O) at 2.7 μm and carbon dioxide (CO_2) at 4.3 μm. The fundamental vibrational band of carbon monoxide (CO) at 4.7 μm and the broad emission feature probably related to C-H bearing molecules can also be recognized around the 3.4–3.5 μm region in some comets. We detect CO_2 in 17 out of 18 comets, and derived gas production rate ratios of CO_2 with respect to H_2O in 17 comets. We detect a reliable CO emission band only in three of the comets. Our data set provides the largest homogeneous database of CO_2/H_2O ratios in comets obtained so far.

Key words: comets: general; infrared: planetary systems: protoplanetary disks

1. INTRODUCTION

Comets are considered to be the most pristine objects in the solar system. One of the main goals of cometary studies is the determination of the composition of volatile ice species contained in the nucleus. Chemical abundances from the cometary ices have been used to infer the conditions in the early solar nebula. One of the most important characteristics of cometary ice is the mixing ratio of major volatiles relative to water (H_2O), especially for carbon dioxide (CO_2), carbon monoxide (CO), and organics. Mixing ratios are thought to provide us with the precious information about the chemical evolution in the early solar nebula. Besides H_2O, CO_2 and CO are the most abundant volatile species in cometary ices. However, because of the severe absorption of telluric CO_2 in the atmosphere, we cannot access the cometary CO_2 with ground-based observations. To date, the daughter species of CO_2 have been used to determine the mixing ratio of CO_2 (see Bockelée-Morvan et al., 2004). In addition, several direct measurements by spacecrafts (Combes et al., 1988; Feaga et al., 2007; A'Hearn et al., 2011) or infrared satellites (Crovisier et al., 1996, 1997, 1999a, 1999b; Colangeli et al., 1999) were available.

Recently, the Japanese infrared satellite AKARI (Murakami et al., 2007) has observed more than a dozen comets in the near-infrared wavelength region, and the mixing ratio of CO_2 with respect to H_2O for the comets are reported (Ootsubo et al., 2010; Ootsubo et al., 2012). In this paper, we summarize the observations and results of the AKARI survey for the mixing ratios of the major volatiles, in particular for CO_2, in comets. As for the AKARI observations of the Solar System objects, the results of the asteroids (Usui et al.,

2012) and the zodiacal light (Pyo et al., 2012) are also reported in this volume.

2. AKARI OBSERVATIONS OF COMETS

The Japanese infrared satellite AKARI (Murakami et al., 2007) was launched on 2006 February 21, and its liquid helium (LHe) cryogen was exhausted on 2007 August 26 UT, 550 days after the launch. In the post-helium phase (called Phase 3), only near-infrared observations have been carried out after 2008 June (Onaka et al., 2010). Near-infrared observations of comets were performed with the Infrared Camera (IRC) onboard AKARI during this post-helium phase mainly as part of the SOSOS Mission Program observations, and several comets were observed as part of the AKARI director's time observations.

The IRC has a spectroscopic capability in both the grism (NG) mode and the prism (NP) mode with the AKARI IRC Astronomical Observation Template (AOT) IRCZ4 in Phase 3. The IRC NG and NP mode can cover the wavelength range from 2.5 to 5 μm and from 1.8 to 5.5 μm, respectively (Onaka et al., 2007; Ohyama et al., 2007), where the vibrational bands of H_2O, CO_2, and CO (at 2.7, 4.3, and 4.7 μm, respectively) are usually recognized as emission in the cometary spectra. The NG mode has a higher spectral resolution than the NP mode and it is suitable for observing the molecular emission bands. By contrast, the NP mode has a higher sensitivity than the NG mode.

Although several comets were observed with the $5''$ slit (Ns), most of the comets were put on the $1' \times 1'$ aperture mask (Np) with the IRC spectroscopy to observe the wide coma regions and minimize the contamination from nearby objects (Ootsubo et al., 2010; Ootsubo et al., 2012). We performed a very careful data reduction for the comets because the objects are moving targets and extended. We use second- or third-order polynomial functions to fit and subtract the continuum component from the spectra. Detailed information about the data reduction for the NG spectroscopic observations of comets is given in Ootsubo et al. (2012).

As a first step, we concentrate on the data taken in the IRC/NG mode with Np window (2.5 to 5 μm). From the 37 pointed NG observations (Table 1), we derived spectra for 18 comets and all the comet spectra are shown in Ootsubo et al. (2012). We also observed several comets in the NP mode, including other comets that are not listed in Table 1, not only with the NG mode. The results of the comets observed in the NP mode will be discussed elsewhere in the near future.

TABLE 1.
Observed Comets with AKARI in NG Mode

Jupiter-family Comets

OBJECT	UT Date	r_h[AU]	Δ[AU]
19P/Borrelly	2008 Dec 30.08	2.19	1.95
22P/Kopff	2009 Apr 22.57	1.61	1.26
22P/Kopff	2009 Apr 22.63	1.61	1.26
22P/Kopff	2009 Dec 11.18	2.42	2.22
22P/Kopff	2009 Dec 11.45	2.43	2.22
22P/Kopff	2009 Dec 11.52	2.43	2.22
29P/Schwassmann-Wachmann	2009 Nov 18.49	6.18	6.09
29P/Schwassmann-Wachmann	2009 Nov 18.56	6.18	6.09
64P/Swift-Gehrels	2009 Nov 23.09	2.27	2.05
64P/Swift-Gehrels	2009 Nov 23.16	2.27	2.05
67P/Churyumov-Gerasimenko	2008 Nov 02.38	1.84	1.56
81P/Wild	2009 Dec 14.10	1.74	1.44
81P/Wild	2009 Dec 14.16	1.74	1.44
81P/Wild	2009 Dec 14.50	1.74	1.43
88P/Howell	2009 Jul 03.06	1.74	1.41
88P/Howell	2009 Jul 03.13	1.73	1.41
116P/Wild	2009 May 15.60	2.22	1.98
116P/Wild	2009 May 16.49	2.22	1.99
118P/Shoemaker-Levy	2009 Sep 08.71	2.18	1.93
118P/Shoemaker-Levy	2009 Sep 08.78	2.18	1.93
144P/Kushida	2009 Apr 18.48	1.70	1.37
144P/Kushida	2009 Apr 18.55	1.70	1.37
157P/Tritton	2009 Dec 30.13	1.48	1.11
157P/Tritton	2009 Dec 30.27	1.48	1.11

Oort Cloud Comets

OBJECT	UT Date	r_h[AU]	Δ[AU]
C/2006 OF2 (Broughton)	2008 Sep 16.72	2.43	2.21
C/2006 OF2 (Broughton)	2009 Mar 28.07	3.20	3.04
C/2006 Q1 (McNaught)	2008 Jun 03.59	2.78	2.59
C/2006 Q1 (McNaught)	2009 Feb 23.76	3.64	3.50
C/2006 W3 (Christensen)	2008 Dec 21.07	3.66	3.52
C/2006 W3 (Christensen)	2009 Jun 16.75	3.13	2.96
C/2007 G1 (LINEAR)	2008 Aug 20.23	2.80	2.62
C/2007 N3 (Lulin)	2009 Feb 05.57	1.28	0.80
C/2007 N3 (Lulin)	2009 Mar 30.67	1.70	1.36
C/2007 Q3 (Siding Spring)	2009 Mar 03.27	3.29	3.14
C/2008 Q3 (Garradd)	2009 Jul 05.60	1.81	1.48
C/2008 Q3 (Garradd)	2009 Jul 06.49	1.81	1.50
C/2008 Q3 (Garradd)	2010 Jan 03.14	2.96	2.78

3. MIXING RATIOS

We detect H_2O in all comets, and CO_2 in 17 out of 18 comets except for the comet 29P/Schwassmann-Wachmann 1. In case of the comet 29P, the spectra were obtained when the object was at around 6 AU from the Sun, and the CO_2 emission was not detected on a 3σ level. This is probably explained by the insufficient evaporation of CO_2 from the ice ($T_{\rm sub} \sim 70$ K), which is in contrast to CO ($T_{\rm sub} \sim 25$ K). We only detect a reliable CO emission band in three of the comets, including the comet 29P. The small number of secure CO detection in the comets is caused by the small fluorescence efficiency of the CO fundamental band at 4.67 μm. We need higher wavelength resolution and sensitivity than AKARI/IRC for the secure detection of CO at 4.7 μm.

We use the single-generation Haser model (Haser, 1957) to estimate the gas production rate from the observed molecular band flux for H_2O, CO_2, and CO. The number density of the molecule "X" (n_X) is represented by

$$n_X(\rho) = \frac{Q(X)}{4\pi v_{\rm exp}\rho^2} \exp\left(-\frac{\rho}{v_{\rm exp}\tau_X}\right), \qquad (1)$$

where $Q(X)$ is the gas production rate of the molecule X (molecules s^{-1}), $v_{\rm exp}$ is the expansion velocity of the gas, ρ is the nucleocentric distance, and τ_X is the photodissociation lifetime of the molecule X (see Bockelée-Morvan et al., 2004 and Ootsubo et al., 2012 for more details).

Based on the gas production rate of H_2O and CO_2 obtained here, we derived the gas production rate ratios (the mixing ratios) of CO_2 with respect to H_2O. Figure 1 illustrates the mixing ratios of CO_2 with respect to H_2O in the 13 comets observed within 2.5 AU from the Sun, where H_2O effectively sublimates from the nucleus of the comet. The difference between the Oort cloud comets (OCs) and the Jupiter-family comets (JFCs) is emphasized in different colors. The mixing ratio of CO_2, with respect to H_2O, spans from several to $\sim 30\%$ in our sample of both the JFCs and the OCs.

In Figure 1, we plot the results of the previous studies for the comet 1P/Halley, 9P/Tempel, and 103P/Hartley, together with our result. The results of these measurements fall within the range of our measurements. The present data set of the large samples confirms the range of the ratios obtained by previous measurements (Bockelée-Morvan et al., 2004).

4. COMPARISON WITH PROTOSTELLAR SAMPLES

The comparison in the mixing ratios of ices between the comets and protostellar samples is important because it is the key to answer the essential questions in comet science. It is still an open question whether or not the interstellar ices were chemically processed in the solar nebula before they were incorporated into the cometary nuclei. As for the CO_2, the AKARI survey gives us the first opportunity to perform such comparison.

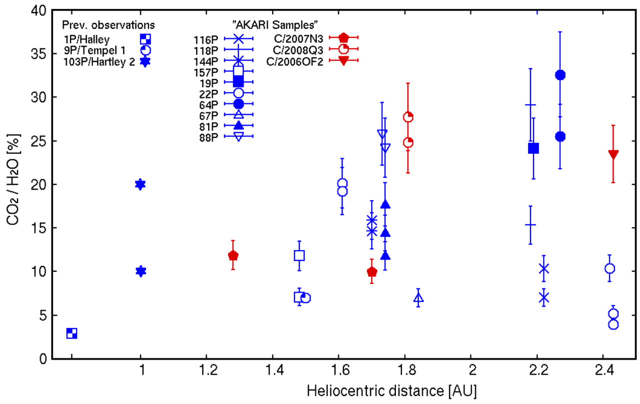

Fig. 1. The mixing ratios of CO_2 with respect to H_2O in the 13 comets observed with AKARI/IRC within 2.5 AU from the Sun. The difference between Oort cloud comets (red) and Jupiter-family comets (blue) are emphasized with different colors. The results obtained with the previous studies before AKARI (1P/Halley, 9P/Tempel, and 103P/Hartley) are also depicted in the figure.

The results for 13 comets observed within 2.5 AU from the Sun show that the range of the CO_2/H_2O ratio in the comets represented by the upper and lower quartile values is 11%–24% (the median value is 17%). In the protostellar samples, the CO_2/H_2O ratios are 22%–35% (the median value is 29%) and 12%–22% (the median value is 13%) as the upper and lower quartile values in the low-mass and high-mass protostar envelopes, respectively (Öberg et al., 2011). The CO_2 in the cometary ice is more depleted with respect to water and more diverse with respect to the median abundance than the low-mass protostellar ices. The CO_2/H_2O ratios in comets seem to be comparable with those in the high-mass protostellar ices rather than with the low-mass protostellar envelope ices. The processes that take place in the high-mass protostar envelopes might also have occurred in the solar nebula disk, such as heating and UV processing by the Sun (Ootsubo et al., 2012, for more detailed discussions).

5. CONCLUDING REMARKS

Both Oort cloud comets and Jupiter-family comets were observed spectroscopically with the Infrared Camera onboard the Japanese infrared satellite AKARI in the period from 2008 June to 2010 January. With the grism mode in the wavelength range from 2.5 to 5 μm, we derived the spectra of 18 comets from 37 pointed observations. Our data set provides the largest homogeneous database of CO_2/H_2O production rate ratios in comets obtained so far. Prominent emission bands of the fundamental vibrational bands of H_2O at 2.7 μm and CO_2 at 4.3 μm can be seen in all comet spectra except for comet 29P/Schwassmann-Wachmann 1.

The gas production rate ratios of CO_2 with respect to H_2O have been derived for 17 comets. The CO_2/H_2O ratio in cometary ice spans from several to $\sim 30\%$ among the comets observed within 2.5 AU from the Sun. The range of CO_2/H_2O ratios is represented by the upper and lower quartile values of 11%–24% (the median value is 17%). These values are comparable to the ones from high-mass protostellar ices (12%–22%). CO_2 in cometary ice is more depleted with respect to water and more diverse than in low-mass protostellar ices. The ices incorporated into comets should have been altered in the early solar nebula, such as the sublimation of CO_2 ice by heating and UV processing by the Sun, assuming that the cometary ice composition has not been altered significantly after the formation of cometary nuclei.

CO was detected only in very few cases. We need a larger comet sample with good CO_2 and CO detctions for further discussions.

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