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Search for sulfur-bearing species as remnant of cometary impact on Neptune

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ABSTRACT

We present the results of CS, OCS, H_2CS, H_2S, SO, C_3S and SO_2 observations in Neptune's stratosphere performed in 2010 and 2013 with the Atacama Sub-millimeter Telescope Experiment 10-m telescope in submillimeter wavebands. Several authors have suggested that CO in Neptune's stratosphere has an external origin and may be due to a previous large cometary impact. To investigate the effects of such impacts, we have conducted new observations to search for various sulfur-bearing species, which are possible remnant gases from the impacts. The CS molecule was likely to be found because CS was observed in Jupiter's stratosphere at least five years after the cometary impact event that occurred in 1994. No sulfur-bearing species was clearly detected in Neptune's upper stratosphere, and their upper limit abundances relative to oxygen were lower than that of both Jupiter's atmosphere observed after the SL9 event and small solar system bodies. From the cometary origin viewpoint, the depletion of sulfur-bearing species found here may be due to their removal from the gas phase by processes such as condensation.

1. Introduction

Neptune's atmosphere is characterized by the presence of abundant gas phase carbon monoxide (CO) (e.g., Rosenqvist et al., 1992). Recently, detailed analyses of the CO line shape have shown that Neptune's upper stratosphere has a larger CO molar fraction than its lower region (Lellouch et al., 2005; Hesman et al., 2007; Fletcher et al., 2010; Luszcz-Cook and dePater, 2013). Such a bimodal vertical distribution implies downward transportation of CO, which originates from an external source. In other words, Neptune's stratosphere is likely to have an external origin. Among other candidates, comets are possible sources of CO. In fact, the collision of comet Shoemaker-Levy 9(SL9) on Jupiter in 1994 produced abundant CO, with total mass was similar to that observed in Neptune's stratosphere (Lellouch et al., 2005). Recently, the cometary origin of CO has been suggested on both Saturn and Uranus (Cavalié and et al., 2010, 2014). Although their derived mixing ratio were smaller than Neptune's case, these new discoveries may suggest that the stratospheres of gaseous planets have some species of cometary origin. For a more comprehensive understanding of the cometary origin and its aftermath on the planetary atmosphere, a further study of Neptune's case is important because its atmosphere is likely to contain a larger amount of cometary originated gases than other planets.

After a large cometary impact, vaporized cometary nuclei deposit various kinds of species in the planetary atmosphere. For the SL9 event, CO, OCS, S_2, CS_2, H_2S, HCN, CS and H_2O were detected in the Jovian stratosphere (e.g., Noll and et al., 1995; Lellouch and et al., 1995; Sprague et al., 1996; Moreno et al., 2001). A similar discovery may be expected in Neptune's case. In particular, we have focused on the sulfur-bearing species in Neptune's stratosphere. In case of the SL9 event, both the S and O atoms in the produced gases were supplied mainly by the comet (Moreno et al., 2003). New findings of S-bearing species whose distribution is limited within Neptune's CO-rich region can support not only the presence of recent cometary impact but also give us new clues to study the sulfur chemistry induced by the cometary impact.

Following the arguments above, we conducted new observations of S-bearing species on Neptune in 2010 and 2013. The first target here was CS, which was the main sulfur reservoir among the remnant gases of the SL9 event (Moreno et al., 2003). Neptune's CS was searched in 2010. We also selected SO_2, H_2S, H_2CS, C_3S, SO and OCS as other sulfur reservoir candidates and searched for them in 2013. In this paper, the observation details are described in Section 2. Radiative transfer processes are in Section 3. Observational results and discussion are presented in Section 4 and 5, respectively.

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2. Observations

Our observations were performed using the Atacama Submillimeter Telescope Experiment (ASTE) 10-m telescope of Japan. ASTE is locating on the Atacama highland, Chile, at an altitude of 4862-m (Ezawa et al., 2004) and is operated by the National Astronomical Observatory of Japan(NAOJ). The observations were performed from 5 to 9 August in 2010, and from 30 September to 2 October in 2013. The observations were operated remotely from the ASTE operation rooms of NAOJ. Neptune's coordinates, apparent diameter, and local standard of the rest velocity (V_{lsr}) for two observation epochs are summarized in Table 1. The ephemeris data were taken from JPL's HORIZON system (Giorgini and et al., 1996). As the front-end, sideband separating (2SB) type SIS heterodyne receiver CATS345 (Inoue et al., 2008) was used. CATS345 can observe in the range 324 to 372 GHz in single side band (SSB) mode. As the back-end, an XF-type 1024-channel spectrometer MAC (Sorai et al., 2000) was used in the 512 MHz bandwidth mode. The frequency resolution corresponding to this setting is 500 kHz. The half power beam width (HPBW) of ASTE is about 22″ at 345 GHz. Observations were performed using a simple on-off position switching method. Off-positions were selected to be separated by ±2′ in the azimuth direction from Neptune's disk itself. Each observation sequence has two on and off positions, each of which has 5 or 15 second integration time. For the intensity calibration, a standard chopper-wheel method (Ulich and Haas, 1976) was employed every 2 or 6 min. Focus adjustments were performed before each observation season. We observed the W51D and Orion KL region before each observation to check the instrument settings. Pointing accuracy was checked with the standard 5-point observation method by observing the nearby point-like CO source χ cygnii and W Aql once every 2 h.

For the data reduction, including data integration, smoothing and baseline correction, the software package NEWSTAR of NAOJ was primarily used. The total integration time for each line is summarized in Table 2. Because the baseline structure of all integrated spectra was corrected using a polynomial fitting method, the averaged intensity of all spectra was set to 0-K level. This process does not affect the narrow emission structure of searched species, which is expected to be 10–50 MHz at 6 mbar. Then, the frequency resolution was smoothed from the originally obtained 500 kHz to 4000 kHz to decrease the noise level.

3. Radiative transfer and atmospheric modelling

For the derivation of abundances of searched S-bearing species, synthesized spectra using a standard one-dimensional line-by-line radiative transfer method were used as a function of abundance and vertical distribution. First, Neptune's disk was divided into a 20 × 20 grid system. Then the Doppler shift velocity and physical atmospheric thickness of each grid were calculated by the plane-parallel geometry. Each grid has 118 vertical atmospheric layers in the range 0.01–6000 mbar pressure level. For the pressure and temperature profile, data obtained from the *Voyager*2 spacecraft were used (Lindal, 1992) below 0.3 mbar. Above 0.3 mbar, the temperature profile used in a previous work (Marten et al., 2005) was used. The opacity of the continuum was calculated from collision-induced absorption of H_2–H_2 and H_2–He pairs (Birnbaum, 1996). Equations for the line opacity calculation are summarized in the Appendix. The parameters for these calculations such as the energy state levels and Einstein coefficients, were obtained from JPL molecular spectroscopy catalog (Picket et al., 1998) and the Cologne Database for Molecular Spectroscopy (Müller et al., 2005) and are listed in Table 2. Because the pressure broadening coefficients γ for most species, except for H_2S and SO_2, were not found in the literature, the value of HCN as 6 MHz/Torr at 300 K was used. For H_2S and SO_2, γ were set to 2 (DeBoer, 1994) and 8 (Bouanich and Blanquet, 1988) MHz/Torr at 300 K, respectively. Each S-bearing species was assumed to be mixed uniformly above 6 mbar, which is equivalent to the CO-rich region derived by Hesman et al. (2007). Although the condensation level of each molecule should be taken into account, they are not considered here because of the absence of parameters needed for the vapor pressure calculation. The calculated spectra for each grid were integrated to reproduce the disk-averaged spectra. Then, the derived disk-averaged spectra were degraded to the antenna temperature scale, which was equivalent to the observed scale. For the main beam efficiency value, a typical value of ASTE, 0.6, was used.

4. Results

4.1. Observation results

The spectra of the searched species are shown in Fig. 1 in black lines. Each window has 512 MHz bandwidth. SO and C_3S are shown in the same window. No clear emission/absorption structure exceeds the 3-σ noise level can be seen for any of the S-bearing species. For the upper limit calculations, we modelled synthesis spectra whose emission intensity is equivalent to 3-σ noise level of obtained spectra and plotted them in Fig. 1 in red lines. Derived upper limit abundances of each S-bearing specie are listed in Table 2.

4.2. Comparison of derived S/O upper limits with other cases

We plotted the obtained upper limit abundances of S-bearing species relative to CO in Fig. 2. For the CO value, we used that obtained in Hesman et al. (2007). For the comparison, the *S/O* values measured in the SL9 event (Moreno et al., 2003) and for small solar system bodies (Anders and Grevesse, 1989; Jessberger et al., 1988; Bockelée-Morvan et al., 2004) are also plotted in Fig. 2. Values for the cometary dust and volatiles are as measured in comets 1P/Halley and C/1995 O1(Hale-Bopp), respectively. For small solar system bodies, while the cometary dust shows a higher *S/O* value than the other two cases and exceeds their error bars, the difference is within a factor of about 5. It is important that the value of the SL9 event is consistent with cometary volatiles and chondrite. Therefore, it is probable that gas produced by a large

Table 1
Observation parameters for Neptune observation.

Date	5–9 August, 2010	30 September–2 October, 2013
Target species	CS, CO, HCN	SO_2, H_2CS, OCS, H_2S, C_3S, CO
Coordinates (RA, DEC)	21 h 59 m 27.80 s, −12 d 47 m 34.5 s	22 h 20 m 24.89 s, −11 d 04 m 51.0 s
Apparent diameter of Neptune	2″.35	2″.34
V_{lsr}	−7.2 km/s	16.9 km/s
Magnetic field rotation period	16.11 ± 0.5 h Warwick et al. (1989)	
Equatorial radius	24,766 km Lindal (1992)	