SUBMILLIMETER OBSERVATION OF JUPITER’S STRATOSPHERIC COMPOSITION: DETECTION OF CARBON MONOSULFIDE (J = 7 – 6) 19 YEARS AFTER THE COMETARY IMPACT

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ABSTRACT

In Jupiter’s stratosphere, gaseous carbon monosulfide (CS) was first discovered in 1994 by millimeter and ultraviolet observations as a product induced by the collision of comet Shoemaker–Levy 9 (SL9). To constrain sulfur chemistry, in 2013, 19 years after the SL9 event, we observed Jupiter’s stratospheric CS J = 7 – 6 rotational transition at 0.8 mm wavelength by using the Atacama Submillimeter Telescope Experiment 10 m single-dish telescope. The CS molecular line was successfully detected with 120 mK intensity in the antenna temperature scale. The obtained CS total mass shows ~90% decrease relative to that observed in 1998. From the line shape analysis, CS is suggested to be present above the 0.2–0.15 mbar pressure level, which is comparable to that determined in 1998.

Key words: planets and satellites: atmospheres – submillimeter: planetary systems

1. BACKGROUND

Cometary impacts are considered to have affected the stratospheric composition of all four gas giant planets. On Jupiter, the 1994 collision of the fragments of comet Shoemaker–Levy 9 (referred to as the SL9 event) caused the delivery of volatile gases such as CO, HCN, H2O, S2, H2S, OCS, CS2, and CS in stratosphere (e.g., Lellouch et al. 1995; Noll et al. 1995; Moreno et al. 2003). Recent submillimeter observations revealed that the upper stratospheric CO molar fraction on Saturn, Uranus, and Neptune is larger than that at the lower levels (Lellouch et al. 2005; Hesman et al. 2007; Cavalié et al. 2009, 2014; Fletcher et al. 2010), which indicates the presence of a CO external supply. On Neptune, since the measured CO/H2O and CO/CO2 flux ratios are larger than the cometary [CO]/[H2O] and [CO]/[CO2] values, the CO was probably formed during a comet impact through shock chemistry rather than a steady influx of interplanetary dust particles (IDPs) and subsequent evaporation (Zahnle 1996). Moreover, observed vertical distribution of the stratospheric CO on Saturn and Uranus match with the cometary impact model, not the IDP model (Cavalié et al. 2010, 2014).

To understand the influence of cometary impact event on the Jovian stratospheric composition, the detailed investigation of the time variation of the mass of the post-SL9 species on Jupiter yield valuable information. We focused on the most abundant sulfur species (CS) and its chemistry because S-bearing species may be diagnostic of cometary impacts in other giant planets as well. After the SL9 event, some S-bearing species were newly discovered in Jupiter’s stratosphere at various wavelengths ranging from ultraviolet to submillimeter. Within a month after the SL9 event, S2 was observed to be a dominant sulfur reservoir among the species discovered, such as CS2, OCS, CS, and possibly H2S (Lellouch et al. 1995; Noll et al. 1995). The abundances of observed S-bearing species have shown different time variations such that while the spectral features of S2, CS2, OCS, and H2S faded within a month (Noll et al. 1995). The CS molecule became a major sulfur reservoir instead. Since the total mass of S2 observed in 1994 as 1014 g was comparable with that of CS in 1995, CS was expected to be produced mainly by the conversion of S2 (Moreno et al. 2003). To explain the conversion of S2 into CS, Moses (1996) developed a sulfur chemistry model such that S2 can produce CS through a reaction with C2H3 as follows: S2 + C2H3 + H → 2CS + 2H2. HCS and H2CS were expected to work as the intermediates to produce CS by the following reactions: HCS + H → CS + H2, H2CS + hν → CS + H2. Frequent millimeter and submillimeter observations of CS, HCN, and CO have been performed from 1994 to 1998 to monitor their abundance, horizontal, and vertical distributions by using the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope and the 15 m James Clerk Maxwell Telescope. Since the total mass of CS measured in 1998 as 1.4 ± 0.6 × 1013 g was within the uncertainty of the value measured in 1995, no time variation of CS abundance was found during the monitoring period. The vertical distribution of CS was modeled as a simple two-layer model with a p0 cut-off pressure level. In 1995, the p0 value was derived to be 0.15 mbar at a longitude of 44°S where the collision sites were located. Owing to the vertical diffusion of gases, the p0 pressure level moved downward to approximately 0.2 mbar and 0.3 mbar in 1996 and 1998, respectively. Moreno et al. (2003) expected the p0 value in 2014 to be 1.0 mbar according to the vertical transportation model.

Besides Jupiter, several attempts have been made to detect S-bearing species on Saturn and Neptune (Fletcher et al. 2012; Iino et al. 2014). However, negative observation results of SO2, H2S, and CS on Saturn, and additional SO, OCS, and C3S on Neptune have been reported. The discrepancies of these results with that of Jupiter’s is interesting, since the cometary impacts on both planets have been suggested as the source of external CO in Saturn and Neptune.
A new observation of CS in Jupiter, 19 years after the SL9 event, could yield important information on the long-term evolution of its abundance and hence on the sulfur chemistry in the Jovian atmosphere. Although the conversion process of \( \text{S}_2 \) into CS occurring just after the impact has already been fully explained (Moses 1996), the sulfur chemistry related to the destruction of the CS is unknown.

In 2013, we conducted a new observation at the submillimeter wavelength, which is typically sensitive to the stratospheric temperature and composition. In this paper, details of the observation, data analysis, and observation results are given in Section 2. The sulfur chemistry in Jupiter’s stratosphere is discussed in Section 3.

2. METHODS

2.1. Observation

Our observation was performed using the Atacama Submillimeter Telescope Experiment (ASTE) 10 m single-dish telescope (Ezawa et al. 2004), operated by National Astronomical Observatory of Japan (NAOJ) and located at an altitude of 4800 m on the Atacama highland, Chile. Observation was performed from 9:36 UT to 11:33 UT, 2013 October 1. The angular diameter of Jupiter was 37\′ 5, whereas the full width at half maximum (FWHM) of the ASTE at the 350 GHz band is 22\′. The observation was conducted during the same period as our Neptune observation (Iino et al. 2014).

We used a sideband separating mixer receiver CATS345 (Inoue et al. 2008) that can be tuned from 324 to 372 GHz. For CS, only the \( J = 7 – 6 \) rotational transition is observable in the frequency range of CATS345. Separation of V and H polarization is not available during the 2013 observation season. For the back end, a MAC XF type digital spectrometer (Sorai et al. 2000) was used with 512 MHz bandwidth and 500 kHz spectral resolution mode. The focus was calibrated before the observing run. Similar to previous observations of Jupiter and Saturn (Moreno et al. 2003; Cavalié et al. 2010), both equatorial edges of Jupiter were set as ON and OFF positions to achieve the high signal-to-noise ratio (S/N) and remove as much as possible the standing waves induced by the observation of a strong and extended continuum source like Jupiter. The integration time for each ON and OFF position was 15 s. For the pointing accuracy correction, cross-scan pointing observation of Jupiter’s continuum emission was performed before and during the observing time. The scanned direction was for azimuth and elevation, and pointing error for both the direction was calculated and calibrated automatically. The measured pointing error during the observation was 1″ and 0″ for azimuth and elevation, respectively, which is better than the 2″−3″ typical pointing error of the ASTE. Owing to the low elevation angle during the observation as 39° 5 − 44° 5, the measured system temperature value of 532−627 K was higher than the typical value of ASTE of 250 K.

Just after the observation, one of the standard sources of ASTE, IRC10216, was observed to calibrate the receiver. The obtained 6.1 K CS intensity of IRC10216 is consistent within 10% with the previous single-sideband calibrated intensity of Caltech Submillimeter Observatory (CSO) (Wang et al. 1994) obtained as 5.7 ± 0.4 K in the antenna temperature scale.

2.2. Observation Results

Figure 1 shows one observation scan after the subtraction of OFF from ON integration. The vertical and horizontal axes are expressed in the antenna temperature scale in units of Kelvin, and the rest frequency in GHz. To decrease the observed baseline structure, the polynomial fitting method was employed for each observation scans. Second, all of baseline-corrected scans equivalent to 47 minutes integration time were averaged. The integrated spectrum is shown in Figure 2 in black lines. The lines seen in the ON and in the OFF spectra (in emission and absorption, respectively, in Figure 2) are blueshifted and redshifted, respectively, because of the planet rapid rotation. The absorption structure is the subtracted emission of the OFF position. The obtained intensities for respective ON and OFF positions are ~120 mK in the antenna temperature scale. The rms noise level achieved here is 18.1 mK. Therefore, detection of the CS line was achieved with 6.6σ confidence.

2.3. Radiative Transfer Analysis of Column Density and Vertical Distribution of CS

For the derivation of the CS abundance and vertical distribution, an atmospheric radiative transfer algorithm developed for terrestrial minor species (Ohyama et al. 2012) was modified and applied to the spectrum. The rest frequency, line intensity, and partition function of CS were extracted from the HITRAN 2012 spectroscopic database (Rothman et al. 2013). The atmospheric structure employed here was the same as in the previous observation (Matthews et al. 2002). The relationship of the pressure-broadening coefficient \( \gamma \) with atmospheric pressure \( p \) and temperature \( T \) is described as follows: \( \gamma = \gamma_0 \times (p/p_0) \times (T_0/T)^n \) cm\(^{-1}\) bar\(^{-1}\), where \( p_0, T_0, n \) are 1 bar, 300 K, and 0.75, respectively, and \( \gamma_0 \) is pressure broadening coefficient of CS at \( p_0 \) and \( T_0 \) as 0.125 cm\(^{-1}\) bar\(^{-1}\). The \( \gamma_0 \) value used here was the same used in the previous study of Moreno et al. (2003) (provided by R.
Moreno 2016, private communication). For the continuum opacity, the collision induced absorption (CIA) of H₂–H₂ and H₂–He pairs were employed for each atmospheric layers. The values of CIA were obtained from the HITRAN catalogue. For the main beam efficiency value, we assumed the typical value of ASTE as 0.6. The spherical geometry was modeled to take into account the limb effect. One-dimensional (1D) radiative transfer calculations were performed on each gridpoint of a grid covering the planet, in which the spacing between gridpoints was set to 100 km (i.e., $\sim 1/720$ equatorial radius). The calculated spectra were averaged assuming the symmetric two-dimensional (2D) Gaussian beam pattern. The calculated opacities of the line center for the equatorial limb and disk center are 0.67 and 0.02, respectively. Various two-layer vertical distribution models in which CS is present uniformly above the $p_0 = 0.01$–1.0 mbar pressure level were attempted to reproduce the obtained spectrum. Only the CS molar fraction was varied as the free parameters and the CS column density was derived from the profile.

### 2.4. Results of Radiative Transfer

From the analysis of the linewidth, we find that the most probable $p_0$ value is 0.2 mbar, which is consistent with the one measured in 1998 as $0.3^{+0.1}_{-0.1}$ mbar (Moreno et al. 2003). 1σ error of $p_0$ range goes from 0.05 to 0.6 mbar region. Corresponding mole fraction and column density of $p_0 = 0.2$ mbar model were $1.1 \times 10^{-9}$ and $3.48 \times 10^{13}$ molecules cm$^{-2}$, respectively. The total mass of CS is $1.6 \times 10^{12}$ g, assuming a horizontally uniform CS distribution, and a surface area with 71492 km equatorial and 61492 km polar radius (Archinal et al. 2011).

We tested the sensitivity of the column density result against the stratospheric temperature. Column densities were calculated for $\pm 6$ and $\pm 3$ K stratospheric temperature models, which include the previously obtained temperature variation from 160 to 166 (Matthews et al. 2002; Moreno et al. 2003). Obtained errors were $3.5^{+1.4}_{-0.8} \times 10^{13}$ molecules cm$^{-2}$ and $3.5^{+0.6}_{-0.6} \times 10^{13}$ molecules cm$^{-2}$ for $\pm 6$ and $\pm 3$ K models, respectively. These values are equivalent to $^{+41}_{-22}$% and $^{+18}_{-17}$% uncertainties. The CS vertical profile for the $p_0 = 0.05$, 0.20, and 0.60 mbar models, $\pm 6$ and $\pm 3$ K stratospheric temperature models are plotted in Figure 3 along with that of CS measured in 1998 (Moreno et al. 2003).

### 3. DISCUSSION

In 1995 May, 10 months after the SL9 event, the CS column density measured at 44°S at the latitude of comet collision was

![Figure 2](image1.png)

**Figure 2.** Left panel: observed (solid black line) and modeled spectra for $p_0 = 0.05$ (thin blue), 0.20 (thick red), and 0.60 (dotted blue) mbar vertical distribution. Right panel: comparison of the best-fit spectra for $+6$ K (dotted blue) and $-6$ K (thin blue) stratospheric temperature ($\Delta T_{\text{strat}}$). $p_0$ is fixed to 0.2 mbar.

![Figure 3](image2.png)

**Figure 3.** Best-fit CS vertical distribution model as $p_0 = 0.20$ mbar and $1.1 \times 10^{-9}$ molar fraction is shown as a thick black line. The $p_0$ value measured in 1998 is consistent with this work. Blue solid and dashed lines are for the $\pm 6$ and $\pm 3$ K stratospheric temperature models, respectively. The CS profile measured in 1998 is plotted in the thin black dashed line with its errors on $p_0$.
reported as \(0.6 - 1.4 \times 10^{15} \text{ cm}^{-2}\) corresponding to a total mass of \(2.0 \pm 1.0 \times 10^{13} \text{ g}\) (Moreno et al. 2003). Figure 4 shows the time variation of CS total mass with respect to the months after the impact. During the long-term monitoring of CS from 1995 to 1998, its total mass did not show a significant change, and the best-fit value throughout the period was reported as \(1.8 \pm 0.4 \times 10^{13} \text{ g}\). Thus, our new observation shows that the CS total mass measured in 2013 decreased by \(\sim 90\%\) when compared with that of 1998. Due to the low S/N, we have not attempted to constrain the temporal variation of the vertical distribution of CS and thus eddy mixing in Jupiter’s stratosphere.

Explaining the decrease of the CS column density is important to understanding the sulfur chemistry in the stratosphere of gas giants. Condensation or polymerization processes may contribute to the removal of CS from the gas phase to produce solid or liquid phase, or polymerized CS expressed as \((\text{CS})_m\). Phase change or polymerization of CS could occur in the stratosphere as the temperature decreases and the number density increases with decreasing altitude. However, the precise evaluation of the phase change is unavailable due to the absence of phase change parameters in the literature. Polymerization is a characteristic phenomenon of S-bearing species. In particular, polymerization of CS on the aerosol surface, which would occur and remove the gas phase CS. The other scenario is that other S-bearing species work as the sulfur reservoir in the deep stratosphere. However, in 1995 and 1996, while some S-bearing species such as H\(_2\)CS, NS, SO, H\(_2\)S, and HNCS were searched already in millimeter waveband, none of them were detected (Moreno et al. 2003).

From the photochemical perspective, the discovery of CS even 19 years after the production is interesting, because CS is considered to be a chemically unstable molecule due to its short lifetime against the photolysis and high reactivity. Photolysis (\(\text{CS} + h\nu \rightarrow \text{C} + \text{S}\)) is the rapid destruction process of CS in the gas phase. Therefore, the discovery of a CS molecule on Jupiter suggests the presence of a strong ultraviolet shielding to prevent the CS photolysis or a recycling process for CS. Photodissociation of CS occurs at wavelength \(\lambda = 1362, 1401, \) and \(1542 \text{ Å}\) (Sanzovo et al. 1993). Since these absorption wavelengths are covered with the photodissociation band of major hydrocarbons such as CH\(_4\), C\(_2\)H\(_4\) and C\(_2\)H\(_6\) (Gladstone et al. 1996), CS photodissociation may be prevented efficiently. Even if the photodissociation occurs, dissociated S-atom could react with hydrocarbon radical rapidly as follows: 
\[
\text{S} + \text{CH}_3 \rightarrow \text{H}_2\text{CS} + \text{H} + \text{CH}_2 \rightarrow \text{HCS} + \text{H}. 
\]
Produced \(\text{H}_2\text{CS}\) and HCS probably photodissociate to produce CS.

In the case of Neptune, a previous large cometary impact is suggested by the larger external flux of CO than that of water vapor (Lellouch et al. 2005; Hesman et al. 2007). The absence of CS (and other S-bearing molecules), as found with ASTE (Iino et al. 2014), could contradict the comet impact hypothesis. However, a detailed sulfur chemistry model should be developed for the further assessment whether the absence of CS is compatible with a comet impact scenario on Neptune (and also on Saturn). Such a model would be helpful in understanding the temporal evolution of the CS mass in Jupiter’s stratosphere. The new development of the detailed sulfur chemistry model includes the precise estimation of ultraviolet shielding and other photochemical processes is helpful. Once the sulfur chemistry on Jupiter is revealed, the result will be a good reference not only to Neptune but also to Saturn where the previous cometary impacts are suggested.

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