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FORMATION OF S-BEARING SPECIES BY VUV/EUV IRRADIATION OF H₂S-CONTAINING ICE MIXTURES: PHOTON ENERGY AND CARBON SOURCE EFFECTS

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ABSTRACT

Carbonyl sulfide (OCS) is a key molecule in astrobiology that acts as a catalyst in peptide synthesis by coupling amino acids. Experimental studies suggest that hydrogen sulfide (H₂S), a precursor of OCS, could be present in astrophysical environments. In the present study, we used a microwave-discharge hydrogen-flow lamp, simulating the interstellar UV field, and a monochromatic synchrotron light beam to irradiate CO:H₂S and CO₂:H₂S ice mixtures at 14 K with vacuum ultraviolet (VUV) or extreme ultraviolet (EUV) photons in order to study the effect of the photon energy and carbon source on the formation mechanisms and production yields of S-containing products (CS₂, OCS, SO₂, etc.). Results show that (1) the photo-induced OCS production efficiency in CO:H₂S ice mixtures is higher than that of CO₂:H₂S ice mixtures; (2) a lower concentration of H₂S enhances the production efficiency of OCS in both ice mixtures; and (3) the formation pathways of CS₂ differ significantly upon VUV and EUV irradiations. Furthermore, CS₂ was produced only after VUV photoprocessing of CO:H₂S ices, while the VUV-induced production of SO₂ occurred only in CO₂:H₂S ice mixtures. More generally, the production yields of OCS, H₂S₂, and CS₂ were studied as a function of the irradiation photon energy. Heavy S-bearing compounds were also observed using mass spectrometry during the warm-up of VUV/EUV-irradiated CO:H₂S ice mixtures. The presence of S-polymers in dust grains may account for the missing sulfur in dense clouds and circumstellar environments.

Key words: astrochemistry – methods: laboratory: molecular – molecular processes – ultraviolet: ISM

1. INTRODUCTION

Theoretical gas-phase chemistry models require very low sulfur abundances in order to match the observations of S-bearing gas-phase molecules in dense molecular clouds (Millar & Herbst 1990). Garozzo et al. (2010) suggested that the missing sulfur is probably locked in icy grain mantles, and later rapidly destroyed to form SO₂ and OCS and other sulfur-bearing molecules by cosmic-ray irradiation. However, there are no observations that support this suggestion; so far, only OCS and tentatively SO₂ have been detected in icy grain mantles (Palumbo et al. 1995, 1997; Boogert et al. 1996, 1997; Zasowski et al. 2009). On the other hand, several S-bearing molecules such as NS, SO, SO₂, H₂S, H₂CS, OCS, and HCS⁺ were observed in the gas phase of hot cores (van der Tak et al. 2003), but current gas-phase chemical models are unable to explain the abundances of some S-bearing molecules like OCS and HCS⁺ observed toward protostars (Doty et al. 2004). One hypothesis is that S-bearing molecules are formed in ice mantles and later released to the gas phase (Grim & Greenberg 1987; Jiménez-Escobar et al. 2011). Laboratory experiments show that S-polymers S₆ through S₈ are present in residues produced from the UV irradiation of H₂O:CO:NH₃:H₂S ices and subsequent warm-up, together with S₅CH₂, S₆CH₂, and c-(S-CH₂-NH-CH₂-NH-CH₂), which are all detected using gas chromatography (Muñoz Caro 2002). More recently, Jiménez-Escobar et al. (2011) reported the formation of S₂ and S₃ in UV-irradiated H₂S and H₂O:H₂S ices, which were observed during subsequent warm-up process. The sulfur dimer, S₂, has also been detected in X-ray-irradiated H₂S ices (Jiménez-Escobar et al. 2012).

The formation of OCS, which was detected in ice mantles due to its unusually high IR band strength, has been studied by the proton irradiation of CO:H₂S, CO₂:H₂S, CO:SO₂, and CO₂:SO₂ ice mixtures (Ferrante et al. 2008; Garozzo et al. 2010). Those experiments show that the production of OCS is more efficient in H₂S-containing ice mixtures than in SO₂-containing ice mixtures. The main purpose of the present study is to identify which ice component and photon energy lead to the production of the highest abundance of OCS. Interestingly, Leman et al. (2004) reported that OCS can catalyze the coupling of amino acids toward the production of peptides. Amino acids are known to form from the vacuum ultraviolet (VUV) and/or extreme ultraviolet (EUV) irradiation of ice mixtures containing H₂O, NH₃, and one or more carbon sources among CO, CO₂, CH₃OH, CH₄, and even naphthalene (C₁₀H₈) (Bernstein et al. 2002; Muñoz Caro et al. 2002; Nuevo et al. 2007, 2008; Chen et al. 2008). In a follow-up to the present work, we plan to study the catalytic role of OCS in the peptide formation in ices of astrophysical interest.

In contrast, solid H₂S has never been identified in the interstellar medium (ISM), probably because its main band overlaps with a feature of CH₃OH (Garozzo et al. 2010; Jiménez-Escobar et al. 2011), one of the most abundant species detected in ice mantles (Dartois et al. 1999; Gibb et al. 2004; Mumma & Charnley 2011; Whittet et al. 2011). In this paper, we report the observation of efficient photodepletion yields for H₂S in CO:H₂S and CO₂:H₂S ice mixtures. The results could explain why this species has not been observed in ice mantles.

Until now, only proton irradiation of ices containing CO or CO₂ as the carbon source and H₂S or SO₂ as the sulfur

Table 1
Band Positions and Band Strengths (A) of the Starting Ice Components Used
and the Photoproducts Identified in This Study

Molecules	Band position (cm^{-1})	A (cm molecule^{-1})	References
H ₂ S	2550	2.0×10^{-17}	Jiménez-Escobar & Muñoz Caro (2011)
CO ₂	2345	7.6×10^{-17}	Yamada & Person (1964)
CO	2139	1.1×10^{-17}	Jiang et al. (1975)
¹³ CO	2092	1.1×10^{-17}	Jiang et al. (1975)
OCS	2050	1.5×10^{-16}	Hudgins et al. (1993)
CS ₂	1520	9.13×10^{-17}	Pugh & Rao (1976)

source have been studied and reported for the formation of OCS (Ferrante et al. 2008; Garozzo et al. 2010). A UV-irradiation study of similar ice mixtures was, to our knowledge, not reported in the literature. In this work, we present a series of experiments using either a microwave-discharge hydrogen-flow lamp (MDHL), referred to as the VUV light source (simulating the interstellar UV field; Gredel et al. 1989; Cruz-Diaz et al. 2014a) or a monochromatic light (at wavelengths of 30.4 nm and 58.4 nm) provided by a synchrotron radiation, referred to as the EUV light source. According to observations, the prominent solar emission intensities at 30.4 nm (He II), 58.4 nm (He I), and 121.6 nm (Ly α) are 3.59×10^{13} , 9.57×10^{12} , and $3.25 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, respectively (Dupree & Reeves 1971). EUV photons can excite molecules to their ionization continua and dissociate them into neutral and ionic fragments, and that some molecular species may be synthesized after irradiation with EUV photons, but not necessarily after vacuum ultraviolet (VUV) irradiation (Wu et al. 2002).

2. EXPERIMENTAL

The experiments described in this work were performed using the Interstellar Photoprocess System (IPS). This setup and the experimental protocol are described in detail in Chen et al. (2014). Briefly, the IPS consists of an ultra-high-vacuum (UHV) chamber equipped with a closed-cycle helium cryostat, with a background pressure of $\sim 1 \times 10^{-10}$ torr. Ice films were deposited on a KBr window, which is attached to the tip of a cold finger. The temperature of the KBr window can be controlled by a tunable heater with a 0.1 K accuracy from 14 K to 400 K.

Gas mixtures were prepared in a gas handling system consisting of four stainless steel bottles of the same volume. The relative proportions between the mixture components were determined by their partial pressures. Gas mixtures were admitted and sprayed onto the KBr substrate in the UHV chamber via 1/4" flexible stainless steel tube, and the flow rate was controlled with a leak valve. The chemical compounds used for these experiments were CO (Matheson, 99.99% purity), ¹³CO (Specialty Gases of America, 99% purity), CO₂ (Matheson, 99.995% purity), and H₂S (Specialty Gases of America, 99.5% purity).

Ice mixtures in the UHV chamber were monitored by an *in situ* Fourier-transform infrared (FTIR) spectrometer equipped with a mercury–cadmium–telluride (MCT) detector and used in its transmission mode. Infrared spectra were acquired with a 4 cm^{-1} resolution and averaged over 128 scans. The photo- and thermo-desorbed species during photon irradiation and warm-up process were detected by quadrupole mass spectrometry (QMS). The column densities of each component of the deposited ice

mixtures and of the photoproducts were calculated according to:

$$N = \int_{\text{band}} \frac{\tau_v dv}{A}, \quad \text{with } \tau_v = \ln(I_0/I), \quad (1)$$

where N is the column density in molecules cm^{-2} , τ_v the optical depth of the band, ν the wavenumber in cm^{-1} , A the band strength in cm molecule^{-1} , and I_0 and I the intensities of the IR beam before and after passing through the ice sample, respectively. The band strengths used for the IR bands of H₂S, CO₂, CO, ¹³CO, OCS, and CS₂ are listed in Table 1. Using the VUV absorption cross sections of CO and CO₂ reported by Cruz-Diaz et al. (2014a, 2014b), we estimated that the VUV photon absorption efficiency of CO ice in the 115–170 nm range is about 1 order of magnitude higher than that of CO₂ ice, so that in this study the column density of the deposited CO₂ was chosen to be about 10 times higher than that of CO.

The MDHL was used to provide VUV photons in the 114–180 nm range and its emission spectra in different operating configurations were discussed in detail in Chen et al. (2014). Typically, the MDHL provides hydrogen Ly α emission (H Ly α , 121.6 nm or 10.2 eV) and molecular H₂ emission in the 110–180 nm range (6.89–11.27 eV). In this study, two operating configurations of the MDHL equipped with MgF₂ and CaF₂ windows were chosen to provide VUV light sources with 8.4% of Ly α (with an average photon energy over the full emission range of 8.6 eV) and 0.0% of Ly α (same average photon energy), respectively, in order to determine the effect of Ly α photons on the photochemistry of CO:H₂S and CO₂:H₂S ice mixtures. The synchrotron radiation was produced by a 1.5 GeV electron storage ring at the National Synchrotron Radiation Research Center (NSRRC) in Hsinchu, Taiwan. The High Flux Cylindrical Grating Monochromator (HF-CGM) beamline provides photons with energies in the 5–45 eV range. A typical bandwidth (FWHM) of 0.4 nm in the EUV region was utilized in the present work. For this study, He I (21.2 eV, 58.4 nm) and He II (40.8 eV, 30.4 nm) were selected, with a photon flux of $\sim 1 \times 10^{14} \text{ photons cm}^{-2} \text{ s}^{-1}$. In order to derive accurate photoproduction yields for products and photodepletion yields for parent molecules, an accurate measurement of the irradiation photon flux is required. Therefore, a calibrated nickel mesh, whose photoelectric efficiency is traceable to NIST standards, was installed *in situ* and was used to continuously record the photon flux during experimental runs.

3. RESULTS AND DISCUSSION

3.1. VUV Photon Irradiation of CO + H₂S and CO₂ + H₂S Ice Mixtures

3.1.1. Photolysis Products and Formation Mechanisms

Figure 1 shows the IR spectra of the CO:H₂S (20:1) and CO₂:H₂S (20:1) ice mixtures before and after VUV irradiation

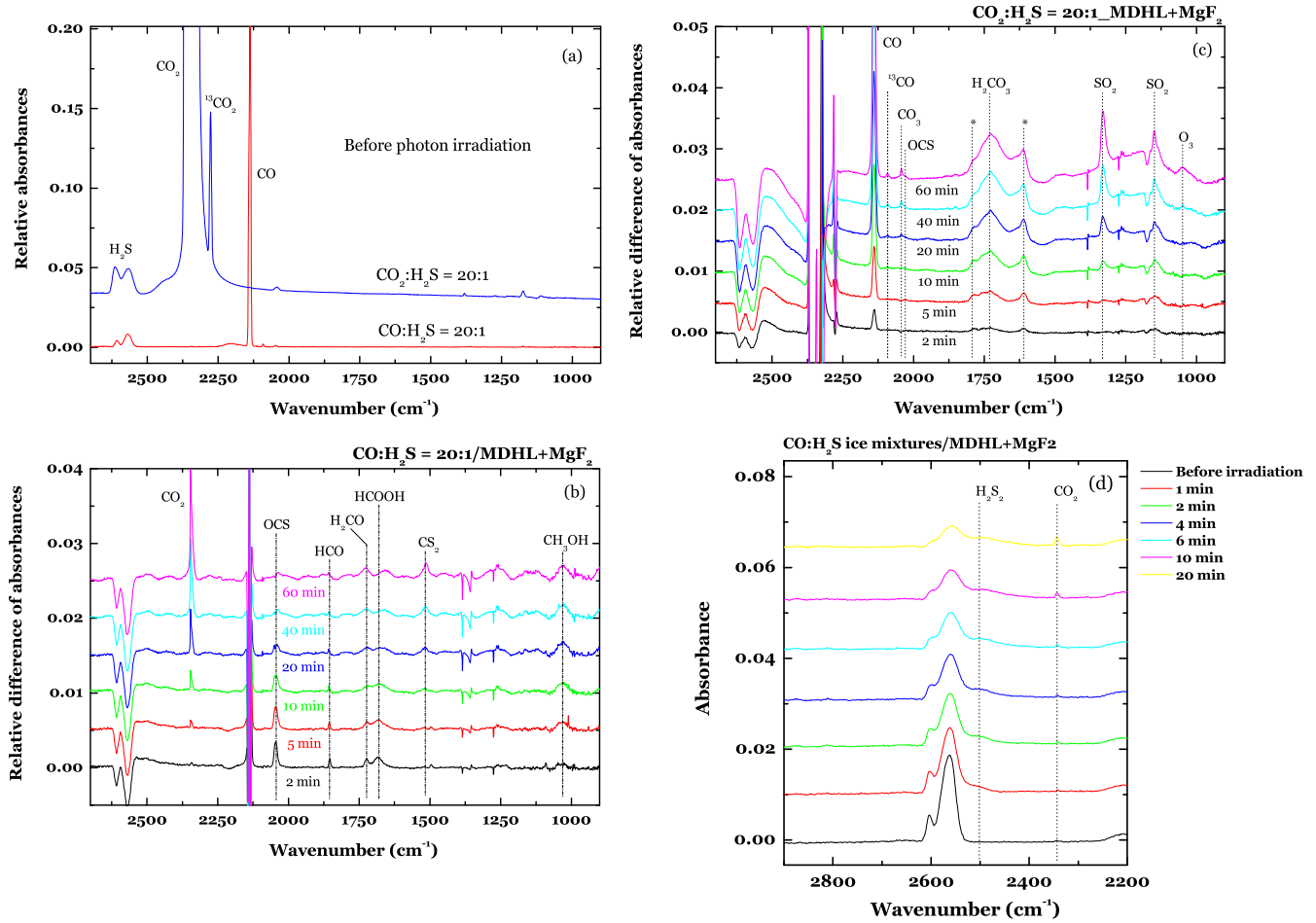
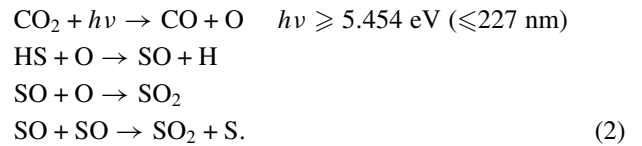


Figure 1. (a) IR spectra of the CO:H₂S = 20:1 and CO₂:H₂S = 20:1 ice mixtures before irradiation with the MDHL + MgF₂. (b) CO:H₂S = 20:1 ice mixture after irradiation. (c) CO₂:H₂S = 20:1 ice mixture after irradiation. (d) IR spectra of the CO:H₂S ice mixtures plotted in absorbance, in order to emphasize the presence of the absorption band assigned to H₂S₂.

(MDHL + MgF₂) at 14 K. The measured spectral positions of products resulting from the VUV irradiation of CO:H₂S (20:1) and CO₂:H₂S (20:1) ice mixtures are listed in Tables 2 and 3, respectively. It must be mentioned that H₂S₂ is not easy to observe in the IR spectra plotted as the difference of absorbances, because its absorption peak overlaps that of H₂S, and thus its intensity is difficult to measure. Therefore, we calculated the absorption area of the H₂S₂ peaks from the IR spectra plotted in absorbance, as the one shown in Figure 1(d). We note that CS₂ was only produced in the VUV-irradiated CO:H₂S ice mixture, while SO₂ was only produced in the VUV-irradiated CO₂:H₂S ice mixture. This result is in agreement with that of Ferrante et al. (2008), who used 0.8 MeV protons to irradiate CO:H₂S (5:1) and CO₂:H₂S (5:1) ice mixtures. However, it is quite different from the results of Garozzo et al. (2010), who used 0.2 MeV protons to irradiate a CO:H₂S (10:1) ice mixture and reported the observation of SO₂, suggesting an effect of the ratio between the components in the starting mixtures.

The VUV light source employed in this study was MDHL equipped with an MgF₂ or a CaF₂ window has a cutoff wavelength at 114 nm (10.87 eV) and 123 nm (10.08 eV), respectively. Both photon energies are lower than the dissociation energy of CO at 11.09 eV (Okabe 1978). Therefore, O atoms cannot be produced in VUV-irradiated CO:H₂S ice mixtures. However, the formation of SO₂ requires an oxygen-rich environment, as it is typically formed via the following reaction pathway (see Figure 2):



This may explain why SO₂ is produced in the MDHL irradiation of CO₂:H₂S ice mixtures, but not when starting with an CO:H₂S ice. In addition to Equation (2), there is another possible reaction

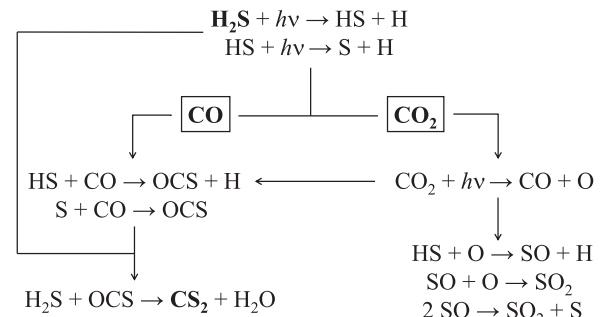


Figure 2. Reaction schemes of the species produced during VUV (MDHL + MgF₂ and MDHL + CaF₂) irradiation of the CO:H₂S and CO₂:H₂S ice mixtures.

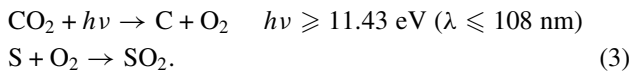
Table 2
Products Identified in the IR Spectra of the CO:H₂S Ice Mixtures Irradiated with 30.4 nm (He II), 58.4 nm (He I), and the MDHL in the Configurations MDFL + MgF₂ and MDHL + CaF₂, and Comparison with Previous Studies

Ice mixture	Present work CO:H ₂ S				Ferrante et al. (2008)	Garozzo et al. (2010)
	20:1	20:1	20:1	20:1	5:1	10:1
Energy source	30.4 nm	58.4 nm	MDHL + MgF ₂	MDHL + CaF ₂	0.8 MeV protons	0.2 MeV protons
Product	Peak position (cm ⁻¹)					
H ₂ S ₂	2511	2511	2510	2508		2487
CO ₂	2344	2344	2346	2345	2342	2345
¹³ CO ₂						2280
C ₃ O ₂	2242	2240			2242	2248
C ₅ O ₂						2214
OCC ¹³ CO	2192	2192				2192
C ₇ O ₂						2122
C ₅ O ₂						2070
OCS	2047	2045	2046	2045	2048	2043
C ₂ O	1988	1988			1990	1989
HCO	1855	1853	1853	1857	1859	1858
H ₂ CO	1716	1722	1724	1723	1712	
HCOOH	1679	1685	1686	1686		
CS ₂	1521	1521	1515	1514	1524	1519
H ₂ CO	1495	1497	1496	1496	1496	
SO ₂						1327
SO ₂						1149
CH ₃ OH	1030	1030	1030	1030		
O ₃						1044

Table 3
Products Identified in the IR Spectra of the CO₂:H₂S Ice Mixtures Irradiated with 30.4 nm (He II), 58.4 nm (He I), and the MDHL in the Configurations MDFL + MgF₂ and MDHL + CaF₂, and Comparison with Previous Study

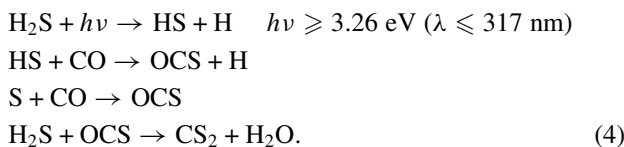
Ice mixture	Present work CO ₂ :H ₂ S				Ferrante et al. (2008)
	20:1	20:1	20:1	20:1	5:1
Energy source	30.4 nm	58.4 nm	MDHL + MgF ₂	MDHL + CaF ₂	0.8 MeV Protons
Product	Peak position (cm ⁻¹)				
H ₂ S ₂ (100 K)	2493	2495	2493	2493	
CO	2140	2140	2139	2141	2142
¹³ CO	2091	2094	2090	2092	
CO ₃	2043	2044	2043	2044	2043
OCS	2040	2040	2042	2042	2048
H ₂ CO ₃	1724	1729	1729	1730	
Uni.	1608	1613	1612	1608	
CS ₂	1523	1519			
SO ₂	1330	1330	1331	1332	1337
SO ₂	1149	1150	1149	1148	1152
O ₃	1045	1046	1049	1048	1044

pathway for its formation:



The photon energy provided by the MDHL light source is clearly not sufficient to produce O₂ from the dissociation of CO₂. However, it is not an issue when EUV photons provided by the tunable synchrotron radiation source are used (see Section 3.2 for discussion).

Regarding the production of CS₂ in the photolysis of CO:H₂S ice mixtures, possible reaction pathways include:



To test the above reaction pathways, we checked the production of H₂O. For this, two separate experiments were conducted on similarly prepared CO:H₂S ice samples, one subjected to VUV irradiation and another not irradiated (i.e., a blank experiment). The absorption band of H₂O spanning from 3000 to 3700 cm⁻¹ and centered at 3370 cm⁻¹ was selected for this study. The resulting column density of H₂O produced by VUV irradiation of CO:H₂S ice is plotted in Figure 3, along with that obtained from the blank experiment. In the latter case, the slight increase in the H₂O column density is attributed to condensation on the ice sample from residual H₂O (gas) inside the UHV chamber. However, from Figure 3, it clearly appears that the column density of H₂O in the CO:H₂S ice sample is much higher after VUV irradiation than that in the blank experiment. Thus, both CS₂ and H₂O are observed after the photolysis of CO:H₂S ice mixtures, which is consistent with the pathway described in

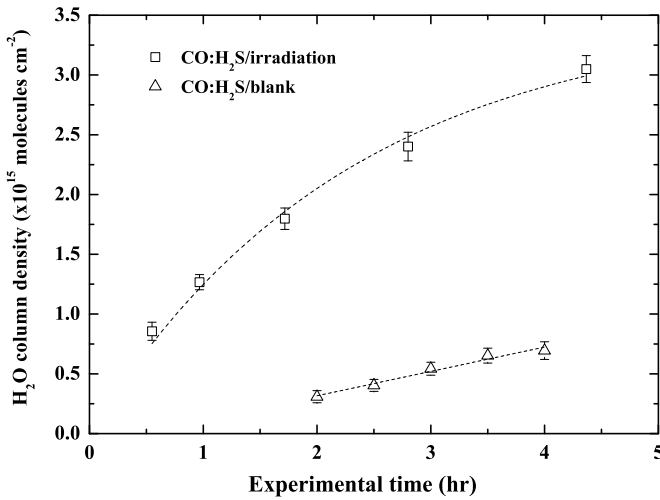
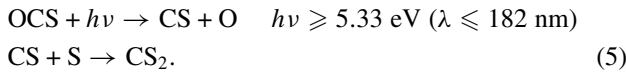


Figure 3. Column density of H₂O as a function of the experimental time for the experiments of the VUV irradiation (MDHL + MgF₂) of the CO:H₂S ice mixtures, and for the blank experiment (no irradiation) of the CO:H₂S ice mixture.

Equation (4). Another possible pathway for the production of CS₂ is:



The CS radical is produced from the subsequent photodissociation of OCS, which competes with the reaction with H₂S (Equation (4)). Thus, this reaction will not contribute significantly to the production of CS₂, simply because the abundance of the starting H₂S molecules will be an order of magnitude higher than that of the produced OCS.

Ferrante et al. (2008) proposed that OCS₂ was produced by 0.8 MeV protons irradiation of pure OCS ice, and subsequent OCS₂ → O + CS₂ dissociation would give CS₂. However, they did not observe OCS₂ formation in the 0.8 MeV protons irradiation of CO + H₂S ice mixtures experiment. Similarly, we could not identify any OCS₂ produced in our experiments of photo-irradiation of CO:H₂S ices.

The productions of OCS and CS₂, and the depletion of the starting compound H₂S upon photolysis of CO:H₂S ice mixtures (20:1 and 5:1), have been investigated in the present study. Figure 4 shows the normalized column densities of OCS and CS₂, i.e., their column densities divided by the initial column density of H₂S (before VUV irradiation), as a function of the photon dose. The depletion of H₂S at the beginning of the VUV irradiation (photon dose < 2.3 × 10¹⁶ photons cm⁻²) of both CO:H₂S ice mixtures is correlated with the production of OCS. When the photon dose reaches 2 × 10¹⁷ photons cm⁻², the column density of H₂S decreases to less than 10% of its initial value. In other words, more than 90% of the initial H₂S is depleted, while small quantities of OCS are produced. The initial production and depletion yields are summarized in Table 5.

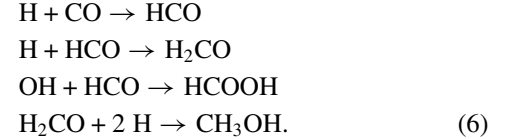
The photo-induced depletion of the starting molecules can result from two independent processes, namely, photolysis and photo-induced desorption (also called photodesorption). Photolysis leads to the destruction of the starting molecules to convert them into products via radical–radical and radical–molecule reactions, whereas photodesorption does not involve any dissociation of the starting molecules but provides them with enough energy to be sputtered out of the ice surface and become free gas-phase particles (Chen et al. 2014). The production of CS₂

Table 4
Identified Products of the MDHL + MgF₂ Irradiation
of the CO:H₂S and ¹³CO:H₂S Ice Mixtures

Ice mixture	Peak position (cm ⁻¹)	
	CO:H ₂ S = 20:1	¹³ CO:H ₂ S = 20:1
H ₂ S ₂	2510	2510
CO ₂	2346	
¹³ CO ₂		2280
OCS	2046	
O ¹³ CS		1994
HCO	1853	
H ¹³ CO		1814
H ₂ CO	1724	
H ₂ ¹³ CO		1687
HCOOH	1686	
H ¹³ COOH		1649
CS ₂	1515	
¹³ CS ₂		1464
CH ₃ OH	1030	
¹³ CH ₃ OH		1018

always begins after the column density of OCS reaches its maximum during the VUV irradiation experiments. This suggests that the formation of CS₂ is correlated with the destruction of OCS, as observed by Ferrante et al. (2008) in their proton irradiation experiments.

The products HCO, H₂CO, HCOOH, and CH₃OH were observed in the irradiated CO:H₂S ices, and were likely formed via the following reactions:



In order to further confirm the identification of the products in the VUV-irradiated CO:H₂S ice mixtures, ¹²CO was substituted by ¹³CO in the sample preparation. Figure 5 shows that the carbon-containing products in the VUV-irradiated (MDHL + MgF₂) CO:H₂S ice, including OCS, HCO, H₂CO, and HCOOH, all display redshifted absorption features in the IR spectra of the VUV-irradiated ¹³CO:H₂S ice experiment, as expected. Table 4 lists the absorption peak positions of all carbon containing products measured in the IR spectra of the VUV-irradiated CO:H₂S and ¹³CO:H₂S ice experiments. It should be noted that Figure 5 does not show the absorption feature of CS₂, because the irradiation time was too short to reach the production column density of OCS required to form CS₂.

3.1.2. Effect of the Carbon Source on the Production of OCS

CO₃ can be produced in irradiated CO₂ ices (Jacox & Milligan 1971; Bennett et al. 2004). Its absorption feature at 2043 cm⁻¹ is close to that of OCS at 2040 cm⁻¹, within the resolution of the present work. The asymmetric absorption band profile between 2080 and 2000 cm⁻¹ could consist of absorption features of both CO₃ and OCS in the irradiated CO₂:H₂S (20:1) ice mixtures (Figure 6). To accurately measure the OCS absorbance and hence its column density, we separated the contributions from both absorption features. For this, the absorption band in the 2080–2000 cm⁻¹ region was deconvoluted with two Gaussian functions. The sum of the two resulting fitted profiles (Figure 6,

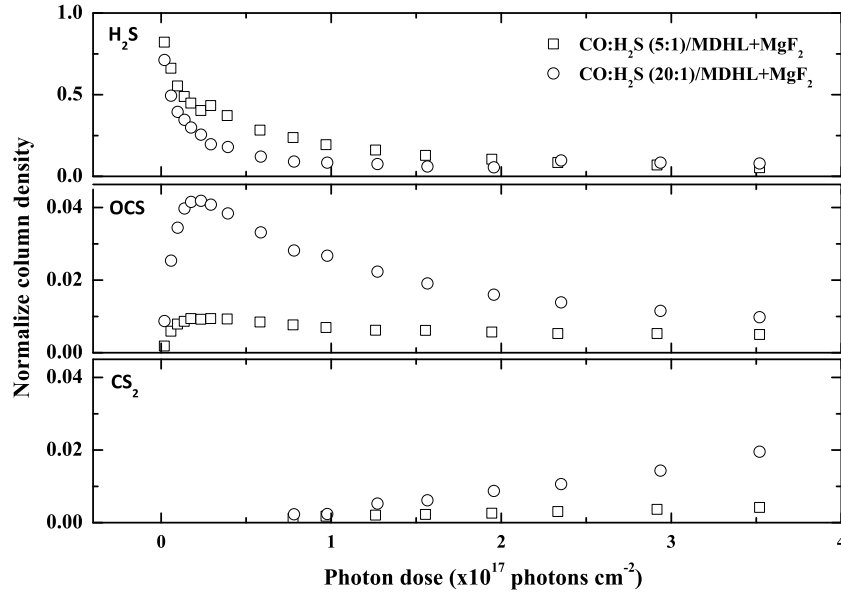


Figure 4. Normalized depletion column density of H_2S and normalized production column densities of OCS and CS_2 in the $\text{CO}:\text{H}_2\text{S} = 5:1$ (squares) and $20:1$ (circles) ice mixtures irradiated with the MDHL + MgF_2 configuration as a function of the photon dose.

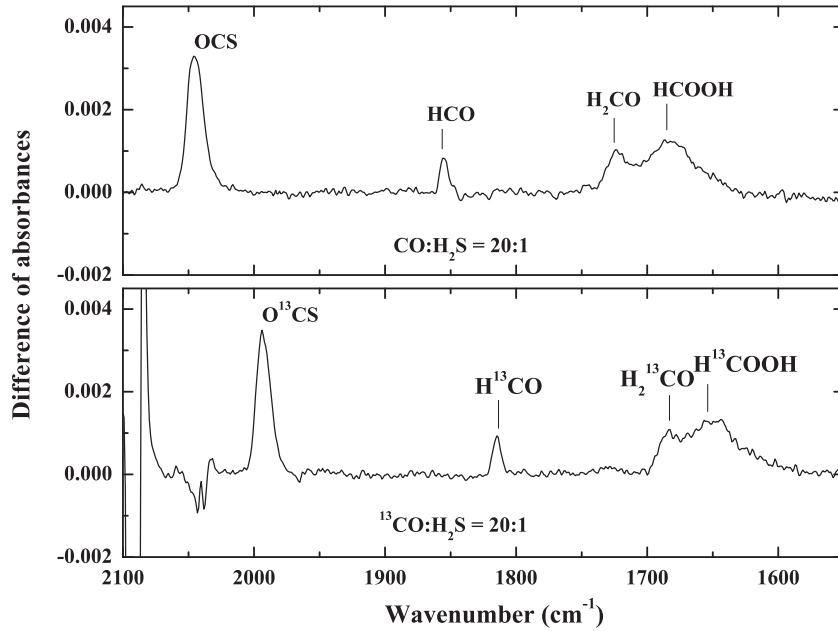


Figure 5. IR spectra of the MDHL + MgF_2 irradiated $\text{CO}:\text{H}_2\text{S}$ (20:1) and $^{13}\text{CO}:\text{H}_2\text{S}$ (20:1) ice mixtures. The bands of ^{13}C -labeled photoproducts are, as expected, shifted to lower wavenumbers.

Table 5
Initial Production Yield of OCS and Depletion Yield of H_2S in the $\text{CO}:\text{H}_2\text{S}$ (20:1) Ice Mixtures Irradiated with the VUV (MDHL + MgF_2 and MDHL + CaF_2) and EUV (30.4 nm and 58.4 nm) Light Sources

		Initial Production Yield of OCS (molecules photon $^{-1}$)	Initial Depletion Yield of H_2S (molecules photon $^{-1}$)
$\text{CO}:\text{H}_2\text{S} = 20:1$	MDHL + MgF_2	$(2.0 \pm 0.2) \times 10^{-2}$	$(1.5 \pm 0.2) \times 10^{-1}$
	MDHL + CaF_2	$(0.8 \pm 0.1) \times 10^{-2}$	$(0.5 \pm 0.1) \times 10^{-1}$
	30.4 nm	$(1.7 \pm 0.2) \times 10^{-2}$	$(1.6 \pm 0.3) \times 10^{-1}$
	58.4 nm	$(0.6 \pm 0.2) \times 10^{-2}$	$(0.4 \pm 0.1) \times 10^{-1}$

red curve) matches the IR band in the spectrum very well (black curve). The sharper peak, centered at 2043 cm^{-1} with a FWHM of 4 cm^{-1} , was assigned to CO_3 , while the broader peak, centered at 2040 cm^{-1} with a FWHM of 20 cm^{-1} , was assigned to OCS . The fitted positions and bandwidths are in very good agreement with previously reported values (Hudgins et al.

1993; Ferrante et al. 2008). The uncertainty for the integrated absorbances was estimated to be better than 5% of the given fitted value.

The column densities of the OCS produced in the VUV-irradiated $\text{CO}:\text{H}_2\text{S}$ (20:1) and $\text{CO}_2:\text{H}_2\text{S}$ (20:1) ices were measured as a function of the photon dose. To present the production

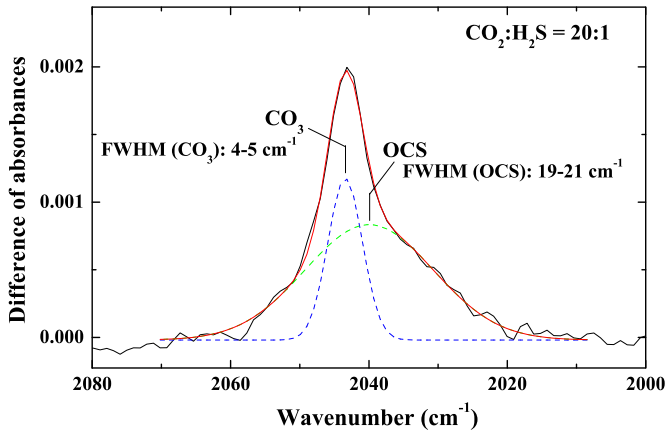


Figure 6. IR spectrum in the 2080–2000 cm^{-1} region of irradiated $\text{CO}_2:\text{H}_2\text{S} = 20:1$ ice showing how the bands of new photoproducts are fitted with Gaussian peaks to identify CO_3 and OCS.

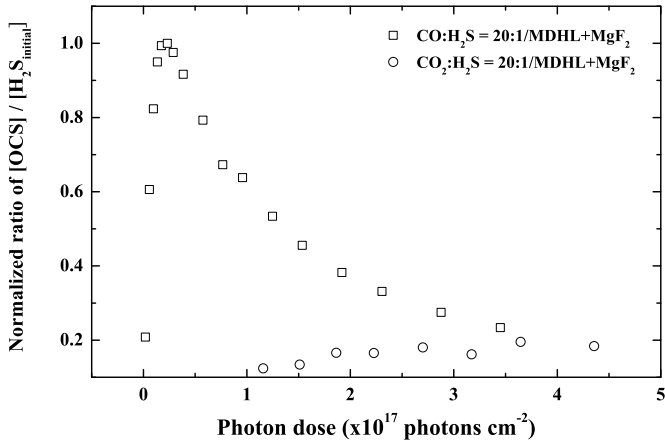
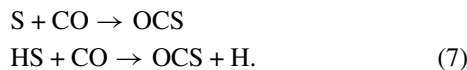
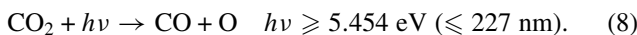


Figure 7. Evolution of the $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$ ratio as a function of the photon dose during the VUV irradiation of $\text{CO}:\text{H}_2\text{S}$ (20:1) and $\text{CO}_2:\text{H}_2\text{S}$ (20:1) ice mixtures. Each data point is normalized to the maximum absorption band area of OCS in the $\text{CO}:\text{H}_2\text{S} = 20:1$ ice mixture.

efficiency of OCS in the VUV irradiation of $\text{CO}:\text{H}_2\text{S} = 20:1$ and $\text{CO}_2:\text{H}_2\text{S} = 20:1$ mixtures, a ratio of $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$, namely, the OCS production column density divided by the initial column density of H_2S , is plotted in Figure 7. The production yield, namely, the number of molecules produced per incident photon, of OCS in $\text{CO}:\text{H}_2\text{S}$ (20:1) ices is at least two orders of magnitude higher than that in $\text{CO}_2:\text{H}_2\text{S}$ (20:1) ices. The maximum conversion of produced OCS from H_2S in the $\text{CO}:\text{H}_2\text{S}$ (20:1) ices is about five times higher than that in the $\text{CO}_2:\text{H}_2\text{S}$ (20:1) ices during VUV irradiation period. Ferrante et al. (2008) and Jiménez-Escobar et al. (2014) proposed the following reaction pathway for the formation of OCS:



When $\text{CO}_2:\text{H}_2\text{S}$ mixtures are used as starting compounds, CO must be formed first via photolysis of CO_2 :



The O atoms produced will subsequently compete with CO to react with HS to form SO radicals. From Equations (7) and (8),

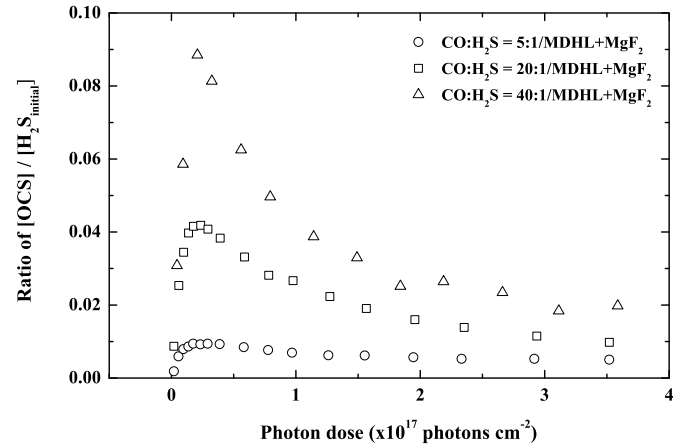


Figure 8. Evolution of the $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$ ratio as a function of the photon dose during the VUV irradiation of the $\text{CO}:\text{H}_2\text{S}$ ice mixtures with relative proportions 5:1 (squares), 20:1 (circles), and 40:1 (triangles).

it is easy to understand why the production yield of OCS in $\text{CO}:\text{H}_2\text{S}$ ices is much higher than that in $\text{CO}_2:\text{H}_2\text{S}$ ices.

3.1.3. Effect of the Concentration of H_2S on the Production of OCS

We have also performed VUV irradiation of $\text{CO}:\text{H}_2\text{S}$ and $\text{CO}_2:\text{H}_2\text{S}$ ice mixtures in several mixed proportions. To estimate the conversion percentage from H_2S into OCS, we have plotted the ratio of column densities $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$ as a function of the photon dose in Figure 8. It shows that the maximum conversion percentage for the sulfur atoms in the starting H_2S into OCS are 4.2% and 1.0% in the VUV-irradiated (MDHL + MgF_2) $\text{CO}:\text{H}_2\text{S}$ (20:1) and $\text{CO}:\text{H}_2\text{S}$ (5:1) ice mixtures, respectively. A lower concentration of H_2S in a VUV-irradiated $\text{CO}:\text{H}_2\text{S}$ ice led to a more efficient formation of OCS. This phenomenon was also observed in VUV-irradiated $\text{CO}_2:\text{H}_2\text{S}$ ice mixtures with starting proportions up to 400:1.

To study how the sulfur concentration in the starting ice mixtures affects the production efficiencies of OCS and H_2S_2 , we set a fixed initial ice column density of CO, so that different relative proportions between CO and H_2S in $\text{CO}:\text{H}_2\text{S}$ ice mixtures will result in a change in the distance between two adjacent H_2S molecules in the ice matrix. Upon VUV photodissociation of H_2S , a shorter distance between two HS radicals would result in their easier recombination, while a longer distance between them would enhance reactions with CO in the ice matrix to form OCS. Since the IR absorption band strength of H_2S_2 is not available in the literature, we present the discussion in terms of the difference in the integrated absorbance, ΔA . Figure 9 shows the plots of ΔA (OCS at 2040 cm^{-1}) and ΔA (H_2S_2 at 2500 cm^{-1}) as a function of the photon dose, and indicates that the evolution of the H_2S_2 production relative to the CO concentration follows an opposite trend to that of OCS. This result supports our expectation that the formation of H_2S_2 competes efficiently with that of OCS, in particular for low CO concentrations. The values of $\Delta A(\text{OCS}) \times \Delta A(\text{H}_2\text{S}_2)$ for $\text{CO}:\text{H}_2\text{S} = 5:1$ and 20:1 ices are 0.0067 and 0.006, respectively, at a photon fluence of $2.4 \times 10^{16} \text{ photons cm}^{-2}$. This is to say that the formation curves for OCS and H_2S_2 in $\text{CO}:\text{H}_2\text{S}$ ices exhibit an anticorrelation relationship.

3.1.4. Effect of the Photon Energy on the Production of OCS

The products are similar in both the $\text{CO}:\text{H}_2\text{S}$ and $\text{CO}_2:\text{H}_2\text{S}$ ice mixtures when irradiated with the MDHL + MgF_2 (8.4% Ly;

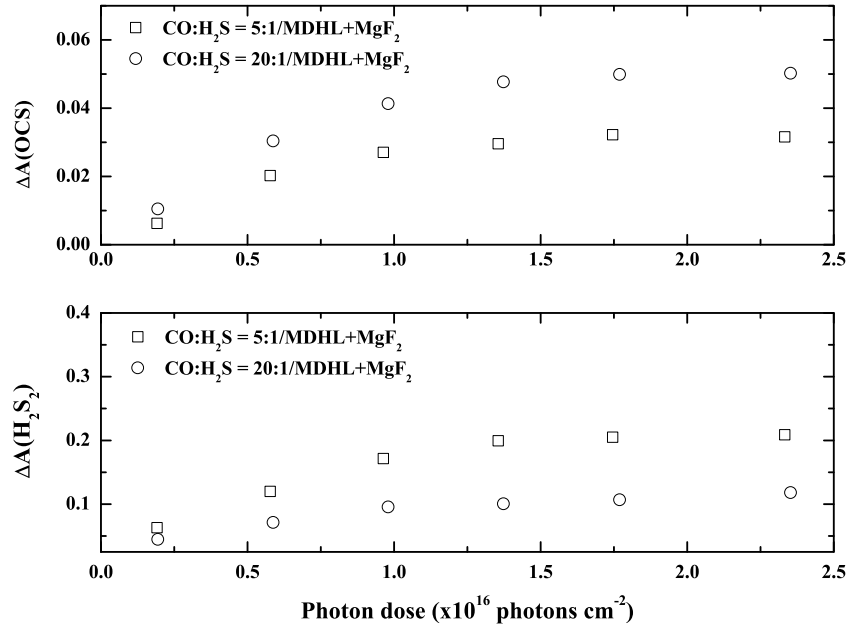


Figure 9. Trends of the difference of absorbances of OCS and H_2S_2 as a function of the photon dose for the VUV-irradiated CO: H_2S (5:1) and CO: H_2S (20:1) ice mixtures.

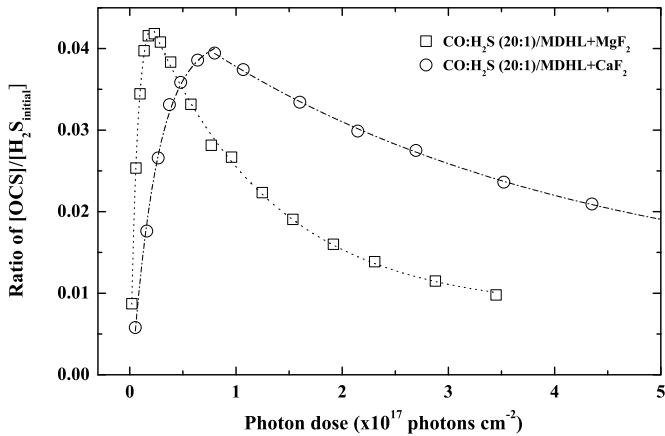


Figure 10. Evolution of the normalized column densities of OCS in the CO: H_2S ice mixtures irradiated with both configurations of VUV light sources (MDHL + MgF_2 and MDHL + CaF_2 , which have different proportions of $\text{Ly}\alpha$ emission), as a function of the photon dose.

average photon energy: 8.6 eV) and MDHL + CaF_2 (0.0% $\text{Ly}\alpha$; same average photon energy) light sources (see Tables 1 and 2). This result can be explained knowing that the dissociation energies of CO, CO_2 , H_2S , and HS are 11.09 eV, 5.5 eV, 3.89 eV, and 3.63 eV, respectively (Okabe 1978; Peebles 2002). Indeed, CO cannot be dissociated upon MDHL irradiation in both operating configurations, but CO_2 , H_2S , and HS are readily dissociated. Therefore, it is not surprising that similar products are formed when CO: H_2S and CO_2 : H_2S ice mixtures are irradiated with VUV photons.

Figure 10 shows the $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$ ratio in the CO: H_2S (20:1) ice mixture irradiated with the MDHL + MgF_2 and MDHL + CaF_2 light sources. The initial OCS production yields determined from Figure 10 are $(2.0 \pm 0.2) \times 10^{-2}$ and $(0.8 \pm 0.1) \times 10^{-2}$ molecules photon $^{-1}$ for the MDHL + MgF_2 and MDHL + CaF_2 configurations, respectively. After OCS reaches its maximum abundance, the depletion yield of OCS upon MDHL + MgF_2 irradiation remains higher than that upon the

MDHL + CaF_2 irradiation. Apparently, in this case the $\text{Ly}\alpha$ photons (8.4% vs. 0% in the two lamp configurations) play an important role in the ice photochemistry.

The absorption cross section of H_2S is almost constant in the 120–160 nm range (Cruz-Diaz et al. 2014a). This observation supports the similar H_2S photodepletion yields measured in both irradiation configurations. In our previous study, the conversion efficiency of CO ice to CO_2 was found to depend on photon energy, i.e., 5% by MDHL + MgF_2 and 12% by MDHL + CaF_2 , respectively (Chen et al. 2014). The absorption cross section of CO ice at 121.6 nm ($\text{Ly}\alpha$) is very small compared to those in the 140–160 nm region (molecular hydrogen emission bands; Lu et al. 2005; Cruz-Diaz et al. 2014a). Therefore, during VUV irradiation, CO molecules in CO: H_2S ice mixture contribute significantly to the production of OCS.

3.2. EUV Photon Irradiation of CO: H_2S and CO_2 : H_2S Ice Mixtures

The effect of EUV irradiation on CO: H_2S and CO_2 : H_2S ice mixtures was studied at NSRRC for two different photon wavelengths, 30.4 nm and 58.4 nm. Figure 11 shows the IR spectra of CO: H_2S (20:1) and CO_2 : H_2S (20:1) ice mixtures at 14 K in the 2400–1000 cm^{-1} region obtained after EUV photon (30.4 nm, He II) irradiation. The photo-products identified in these irradiated ices are listed in Tables 1 and 2, respectively. There is a strong absorption feature around 1613 cm^{-1} which remains to be identified and was also observed in VUV-irradiated CO_2 : H_2S (20:1) ices (see bottom panel of Figure 1c).

A closer look at the IR spectra shown in the top and bottom panels of Figures 11 reveals the striking ice photochemistry at work in the CO: H_2S (20:1) and CO_2 : H_2S (20:1) ice mixtures. CS_2 was observed in both ice mixtures, while O_3 and SO_2 were only detected in the EUV-irradiated CO_2 : H_2S ices. To better compare the data obtained between VUV and EUV irradiation, the $[\text{OCS}]/[\text{H}_2\text{S}_{\text{initial}}]$ and $[\text{CS}_2]/[\text{H}_2\text{S}_{\text{initial}}]$ ratios were plotted as a function of the photon dose in Figure 12. As discussed earlier, in the VUV-irradiation experiments, CS_2 was only produced in the CO: H_2S ice mixtures, and only after a significant

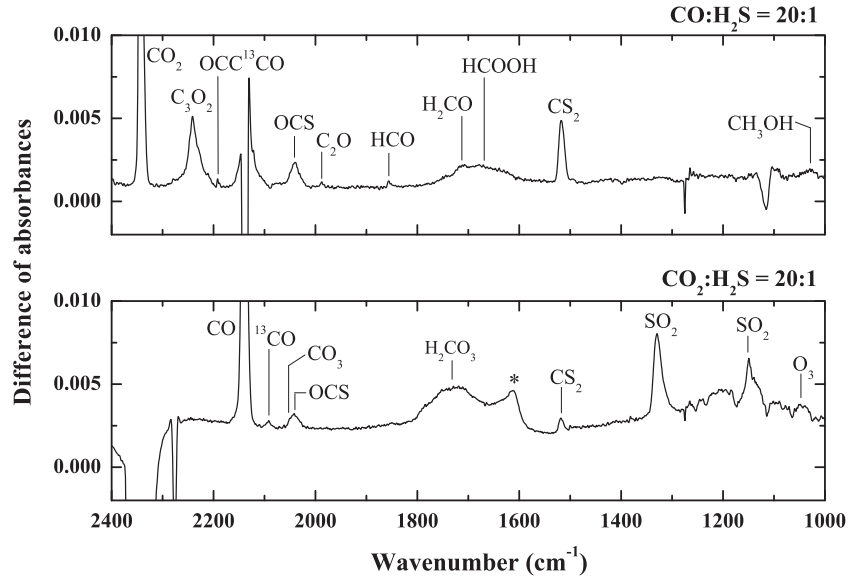


Figure 11. IR spectra of the CO:H₂S = 20:1 (top panel) and CO₂:H₂S = 20:1 ice mixtures (bottom panel) obtained after 30.4 nm photon irradiation.

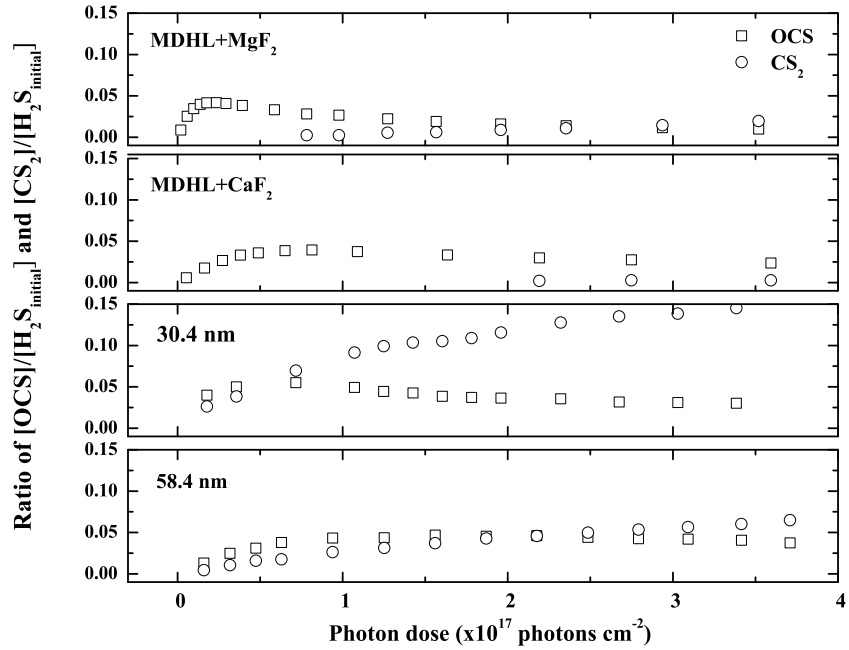
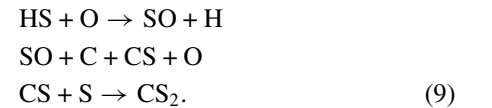


Figure 12. Evolution of the column densities of OCS and CS₂ in the CO:H₂S = 20:1 ice mixtures irradiated with the different light sources employed in the present study as a function of the photon dose.

amount of OCS was formed, which subsequently reacts with H₂S (see the top two panels of Figures 4 and 12). In contrast, in EUV-irradiation experiments, CS₂ is readily produced at the beginning of the irradiation of the CO:H₂S ice mixtures as well as in the CO₂:H₂S ice mixtures. Furthermore, Figure 12 shows that in the cases of 30.4 nm and 58.4 nm irradiations of CO:H₂S (20:1) ice, the production column density of CS₂ increases even when the column density of the produced OCS starts to decrease. The maximum production yield of CS₂ is about three times higher than that of OCS in the 30.4 nm irradiation experiment, which suggests that OCS is not necessarily required for the formation of CS₂ in the EUV irradiation experiments. Since the dissociation energy of CO is 11.09 eV, as mentioned earlier, it can be dissociated to form C and O upon EUV irradiation in both CO and CO₂ containing ice mixtures. The formation of CS₂ in

EUV-irradiated CO:H₂S and CO₂:H₂S ice mixtures can occur via Equations (4) and (5), as well as the following additional reaction pathway:



The HS radicals and S atoms produced from EUV photo-dissociated H₂S have been highlighted in Figures 2 and 13.

The influence of the carbon source and of the H₂S concentration on the production of OCS is comparable in EUV and VUV irradiation experiments. The production yield of OCS from the EUV irradiation of CO:H₂S ices is higher than for CO₂:H₂S ices. The initial production yields of OCS for 30.4 nm and 58.4 nm irradiations of CO:H₂S (20:1) ices were calculated

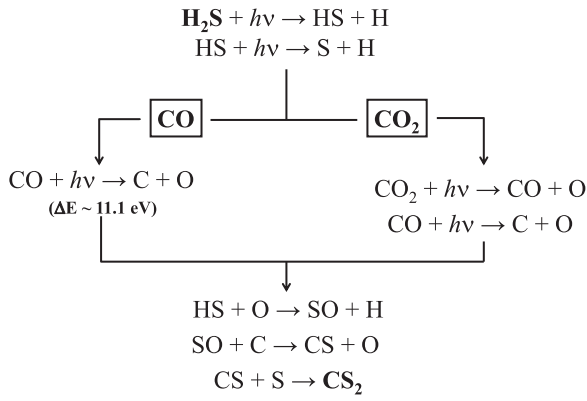


Figure 13. Reaction schemes of the species produced during EUV irradiation (30.4 nm and 58.4 nm) of the CO:H₂S and CO₂:H₂S ice mixtures.

to be $(1.7 \pm 0.2) \times 10^{-2}$ and $(0.6 \pm 0.1) \times 10^{-2}$ molecules photon⁻¹, respectively, indicating that a low concentration of H₂S in the CO:H₂S ice mixtures leads to a more efficient OCS formation.

3.3. The Missing Sulfur Atoms

In this section, we will determine the total conversion of H₂S in CO:H₂S (20:1) ice mixtures into S-containing products. As summarized in Table 1, the S-containing products we are interested in include H₂S₂, OCS, and CS₂. The conversion efficiency can be defined as the sum of the production column densities for H₂S₂, OCS, and CS₂ divided by the initial column density of H₂S, i.e., H₂S_{initial}. In this estimate, the contribution from H₂S₂ was not included because its infrared band strength is not known, so that the conversion data derived here represents only a lower limit. The results are plotted in Figure 14, and show that this conversion efficiency is lower than 5% for the VUV irradiation (MDHL + MgF₂) of a CO:H₂S (20:1) ice mixture (Figure 14(a)), while it is lower than 17% in the case of the 30.4 nm irradiation (Figure 14(b)). The conversion efficiency of S atoms from H₂S in the ice mixtures into S-containing photo-products is higher when 30.4 nm photons are used than in the case of an irradiation with the MDHL. These results are consistent with the fact that higher amounts of CS₂ are produced upon EUV irradiation (compare Figures 12 and 14(b)).

This raises a question about the missing S atoms in the photolysis of CO:H₂S and CO₂:H₂S ices. Barnes et al. (1974) reported that S- or HS-containing species such as H₂S₂ and S₂ are responsible for the formation of S-polymers up to S₈. Palumbo et al. (1997) suggested that S₈ might be formed by UV or cosmic-ray processing of sulfur-bearing molecules in icy grain mantles. However, since S₈ is a monovalent crystal, it has no IR active modes. Therefore, it cannot be detected directly via astronomical observations. Muñoz Caro (2002) reported that the UV irradiation of H₂S ice leads to the formation of S-polymers, which were detected in the resulting residues at room temperature by chromatographic techniques. Jiménez-Escobar & Muñoz Caro (2011) detected S₂ and S₃ in UV-irradiated H₂S and H₂O:H₂S ices during warm-up of their photolyzed ices by utilizing a mass spectrometer.

In order to verify whether other sulfur-bearing molecules are also present in our photolyzed ices, we have performed experiments using the VUV light source (MDHL + MgF₂) to irradiate a pure H₂S ice and a CO:H₂S (20:1) ice mixture. After a total photon dose of 2×10^{18} photons cm⁻², the ices were allowed to slowly warm up at a rate of 2 K min⁻¹

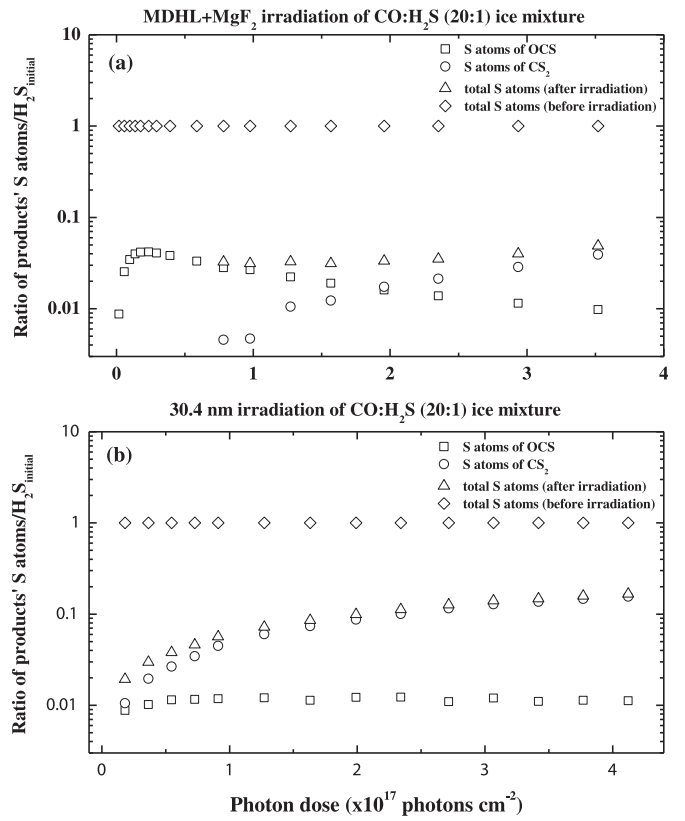


Figure 14. Ratio of the total and partial production column densities of S atoms in sulfur-containing products to the initial column density of H₂S in the CO:H₂S = 20:1 ice mixtures as a function of the photon dose: (a) MDHL + MgF₂ and (b) 30.4 nm irradiation.

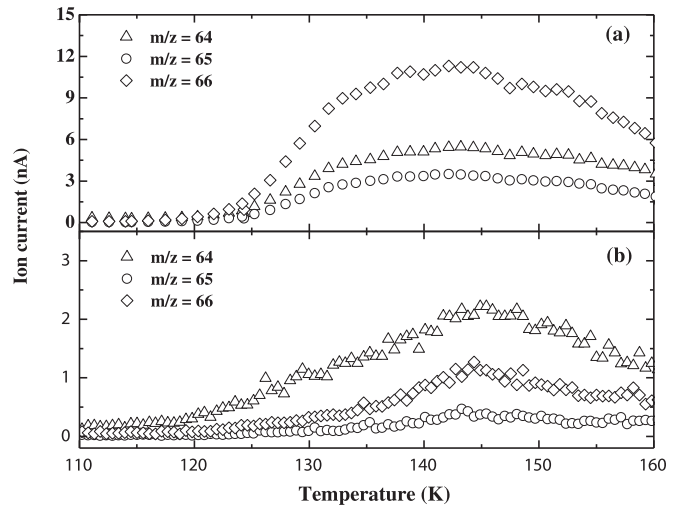


Figure 15. Evolution of the ion currents for $m/z = 64$, 65, and 66 (corresponding to S₂, HS₂, and H₂S₂, respectively) during the warm-up of the photolyzed ices of (a) pure H₂S ice and (b) CO:H₂S (20:1) ice mixtures after irradiation with the MDHL + MgF₂ light source.

and the desorbed gases were monitored by a quadrupole mass spectrometer (QMS). The ion currents measured by the QMS for $m/z = 64$, 65, and 66 (corresponding to S₂, HS₂, and H₂S₂) as a function of the lapse of warm-up time are shown in Figure 15. In the case of the photolyzed ices of pure H₂S ice the signals for ion currents at $m/z = 64$, 65, and 66 are in relative proportions of 0.48:0.31:1, indicating that H₂S₂ ($m/z = 66$) is the most abundant species. The signals of these ion currents reach a

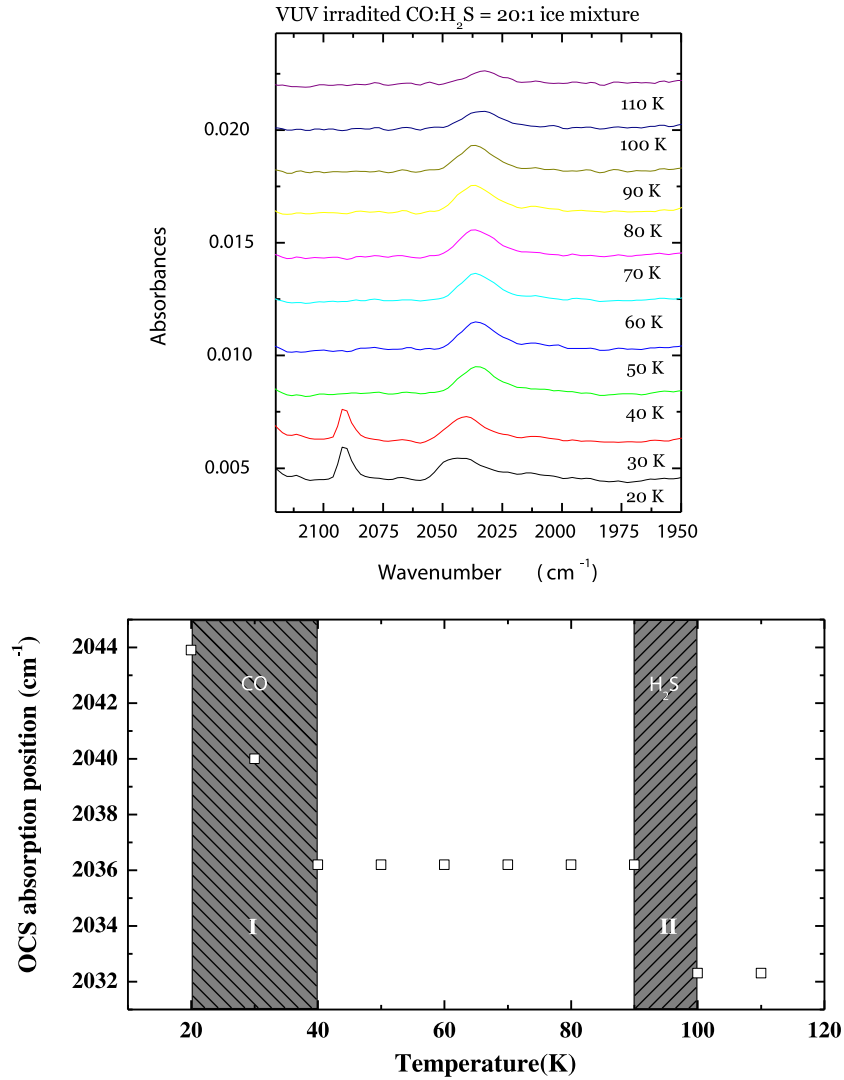


Figure 16. Measured infrared band positions of OCS in CO:H₂S = 20:1 ices after photolysis as a function of the temperature during ice warm-up. Regions I and II (shaded areas in the bottom panel) refer to the sublimation temperature ranges for CO and H₂S, respectively.

maximum around a temperature of 135–145 K. In the case of the irradiated CO:H₂S (20:1) ice mixture, the ion currents at $m/z = 64$, 65, and 66 during warm-up are plotted in Figure 15(b). As can be seen, the ion current for $m/z = 64$ is the highest. This result implies that there is at least one more species in the ice samples contributing to the signal of $m/z = 64$ (namely, S₂). The maximum signal of the ion currents centers around 140–150 K, which appears to agree with the observation of S₂ fluorescence during warm up by Grim et al. (1987), who reported a thermal-desorption temperature for S₂ around 150 K. Therefore, in the present work a fraction of the missing S atoms might be released in the form of S₂ from the photolyzed S-bearing products.

3.4. Effect of the Temperature on the OCS Spectra

In this study, the infrared band position of OCS was measured in CO:H₂S and CO₂:H₂S ice mixtures after irradiation when a total photon dose of 1×10^{18} photons cm⁻² was reached. The results show that in CO:H₂S ices, these band positions depend on the temperature of the ice and the relative proportions between CO and H₂S in the starting mixture. The OCS band at 2044 cm⁻¹ is redshifted as the temperature increases from 20 K to 110 K (Figure 16). In the 20–40 K temperature region during which

CO starts to sublimate, the position of the OCS band shifts from 2044 cm⁻¹ to 2036 cm⁻¹ in the CO:H₂S (20:1) ice. In the 90–100 K region, during which H₂S sublimates, the position of the OCS band shifts from 2036 cm⁻¹ to 2032 cm⁻¹. In contrast, the position of the OCS band at 2042 cm⁻¹ does not change in the same temperature range in the CO₂:H₂S ice mixtures, regardless of the relative proportions between CO₂ and H₂S, which range from 400:1 to 5:1. Such a temperature-dependent data set may help unveil the thermal history of ice mixtures containing OCS molecules.

4. CONCLUSIONS AND RELEVANCE TO ASTRONOMICAL OBSERVATIONS

In this work, we studied the effects of the hydrogen sulfide concentration and the photon energy on the production of photoproducts from the irradiation of CO:H₂S and CO₂:H₂S ice mixtures. Our experimental results show that the depletion of the starting H₂S in CO:H₂S (20:1) and CO₂:H₂S (20:1) ices is rapid and reaches 90% even after irradiation with relatively low photon doses ($\sim 2 \times 10^{17}$ photons cm⁻²), which may explain why H₂S has not been observed in the solid phase in the ISM. The production yield of the photoproduct OCS reaches

maxima of about 5% and 1% relative to the initial S-atom content in CO:H₂S (20:1) and CO₂:H₂S (5:1) ices, respectively. This yield depends on the carbon source, as it is formed more efficiently in CO:H₂S ices than in CO₂:H₂S ices, as well as on the concentration of starting H₂S, as it increases when the concentration of H₂S decreases. One likely explanation for this is that the formation of OCS competes with that of H₂S₂. However, the total production of OCS seems to be independent of the photon energy range (VUV or EUV) of the incident light source, regardless of the relative proportions between the ice components in CO:H₂S and CO₂:H₂S mixtures.

OCS₂, a possible precursor of CS₂, was not observed in any of the CO:H₂S and CO₂:H₂S ice mixtures irradiated with VUV or EUV photons. In contrast, CS₂ where observed, probably formed from the reaction of OCS with H₂S, though its formation mechanism in EUV-irradiation experiments differs from that in the VUV-irradiation experiments. The main difference comes from the fact that CO, a precursor of CS₂, can only be dissociated by EUV photons because the energy of VUV photons is too low. The production yield of CS₂ was found to be higher than that of OCS in the EUV irradiation experiments, which is in agreement with previous experiments of irradiation of CO:H₂S (10:1) ices with 0.2 MeV protons.

The total quantities of detected S-containing products only amount for 5% and 17% of the S atoms in the starting CO:H₂S ices irradiated by VUV and EUV photons, respectively. S₂ was detected at a temperature of ~150 K during the warm-up of the photo-irradiated CO:H₂S ices, but no heavier S-polymers were observed, probably because of their low volatilities.

UV and X-ray irradiation of H₂S in the ice mixtures are known to lead to the production of H₂S₂, which can subsequently be photodissociated into S₂, and could explain the detection of S₂ in comets (Jiménez-Escobar & Muñoz Caro 2011; Jiménez-Escobar et al. 2012). In addition, CS₂ was also proposed as a parent molecule for S₂ in comets (A'Hearn et al. 1983), so that S₂, together with heavier S-polymers, may be formed on the surface of cold, ice-covered grains via VUV, EUV, and/or X-ray irradiation of mixtures containing H₂S and CO/CO₂.

Comparison between the IR spectra of ices observed toward the protostellar sources AFGL 989, Mon R2 IRS 2, and W33A with laboratory data of ices shows that the best fit to the astronomical observations is obtained if ices include OCS in the H₂O:CH₃OH mixtures (Palumbo et al. 1997). Experiments of irradiation of H₂O:CO:H₂S ices with 0.8 MeV protons indicated that the position of the IR band of the produced OCS was a very good match to that observed in the spectra of W33A at 4.90 μm (Ferrante et al. 2008). In the present work, the band position was found to vary significantly with the temperature during the warm-up after irradiation of the ices, ranging from 2044 cm⁻¹ at 20 K to 2040 cm⁻¹ at 30 K, which is in good agreement with the 2041 cm⁻¹ feature for OCS observed toward W33A (Palumbo et al. 1997). Finally, our laboratory results support the abundance ratio N(CO)/N(OCS) of 20 in W33A estimated by Palumbo et al. (1997).

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