LARGE SILICON ABUNDANCE IN PHOTODISSOCIATION REGIONS

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ABSTRACT

We have made one-dimensional raster scan observations of the ρ Oph and σ Sco star-forming regions with two spectrometers (SWS and LWS) on board the ISO. In the ρ Oph region, [Si ii] 35 μm, [O i] 63 μm, 146 μm, [C ii] 158 μm, and the H2 pure rotational transition lines S(0) to S(3) are detected, and the photodissociation region (PDR) properties are derived as the radiation field scaled by the solar neighborhood value G0 ~ 30–500, the gas density n ~ 250–2500 cm−3, and the temperature T ~ 100–400 K. The ratio of [Si ii] 35 μm to [O i] 146 μm indicates that silicon of 10%–20% of the solar abundance must be in the gaseous form in the PDR, suggesting that efficient dust destruction is ongoing even in the PDR and that a fraction of the silicon atoms may be contained in volatile forms in dust grains. The [O i] 63 μm and [C ii] 158 μm emissions are too weak relative to [O i] 146 μm to be accounted for by standard PDR models. We propose a simple model, in which overlapping PDR clouds along the line of sight absorb the [O i] 63 μm and [C ii] 158 μm emissions, and show that the proposed model reproduces the observed line intensities fairly well. In the σ Sco region, we have detected three fine-structure lines, [O i] 63 μm, [N ii] 122 μm, and [C ii] 158 μm, and derived that 30%–80% of the [C ii] emission comes from the ionized gas. The upper limit of the [Si ii] 35 μm is compatible with the solar abundance relative to nitrogen, and no useful constraint on the gaseous Si is obtained for the σ Sco region.

Subject headings: infrared: ISM — ISM: individual (ρ Ophiuchi Cloud) — ISM: lines and bands

1 INTRODUCTION

Silicon and carbon are major constituents of interstellar grains (Mathis 1990). The gas-phase Si abundance is about 5% of solar in cool clouds (Savage & Sembach 1996), and the depleted atoms are thought to reside in interstellar ice. According to the observations of UV absorption lines, Si shows a systematic trend of depletion with the density of the diffuse cloud, as well as Mg and Fe (Jenkins et al. 1986; Harris et al. 1984), whereas the depletion of Fe seems not to continue to increase with either density or extinction for ⟨ns⟩ ≥ 1 cm−3 (Snow et al. 2002). Sofia et al. (1994) suggested that Fe has the greatest fraction of its atoms incorporated into dust, followed by Mg and Si, and suggested oxides and/or metallic Fe as the grain core population. Fitzpatrick (1996) showed that the gas-phase abundances of Si and Fe are well correlated with each other to some extent, but the degree of returning to the gas phase is different between the two: it is easier for Si to return to the gas than for Fe. This suggests that at least a fraction of Si and Fe atoms constitute independent grain populations. Jones (2000) examined the relation among the depletions of Si, Mg, and Fe, suggesting that Si in dust is preferentially eroded with respect to Mg and that both of these elements are preferentially eroded with respect to Fe. This cannot be completely explained by a mechanical sputtering process, indicating some chemically selective processes involved or the presence of Si in phases other than refractory silicates. Frisch & Slavin (2003) showed that the gas-to-dust ratio in the local ISM is well correlated with the fraction of the dust mass carried by Fe. This indicates that Fe forms a robust core that is not destroyed during grain processing in the ISM. Cartledge et al. (2004) showed that the dust-ephase abundance of O derived with the “missing mass” method is consistent with the grain model in which silicates are primarily Mg based and most or all of Fe is in metal or oxides. On the other hand, C, N, and O abundance is relatively constant against the gas density (Sofia et al. 1997; Cardelli et al. 1996; André et al. 2003; Jensen et al. 2005), although a dependence on the density for oxygen is also reported (Cartledge et al. 2001, 2004).

Depletion in active star-forming regions, where the density is much higher than in diffuse clouds, has been studied by infrared line emissions. Intense [Si ii] 35 μm emission has been reported in a shocked region in Orion (Haas et al. 1991), the Galactic center region (Stolovy et al. 1995), the Carina region (Mizutani et al. 2001), and the surface temperature T ~ 100–400 K. The ratio of [Si ii] 35 μm to [O i] 146 μm indicates that silicon of 10%–20% of the solar abundance must be in the gaseous form in the PDR, suggesting that efficient dust destruction is ongoing even in the PDR and that a fraction of the silicon atoms may be contained in volatile forms in dust grains. The [O i] 63 μm and [C ii] 158 μm emissions are too weak relative to [O i] 146 μm to be accounted for by standard PDR models. We propose a simple model, in which overlapping PDR clouds along the line of sight absorb the [O i] 63 μm and [C ii] 158 μm emissions, and show that the proposed model reproduces the observed line intensities fairly well.

In the σ Sco region, we have detected three fine-structure lines, [O i] 63 μm, [N ii] 122 μm, and [C ii] 158 μm, and derived that 30%–80% of the [C ii] emission comes from the ionized gas. The upper limit of the [Si ii] 35 μm is compatible with the solar abundance relative to nitrogen, and no useful constraint on the gaseous Si is obtained for the σ Sco region.

Subject headings: infrared: ISM — ISM: individual (ρ Ophiuchi Cloud) — ISM: lines and bands

1 Based on observations with ISO, an ESA project with instruments funded by ESA member states (especially the PI countries: France, Germany, the Netherlands, and the UK) and with the participation of ISAS and NASA.
2004), and the starburst galaxy NGC 253 (Carral et al. 1994). Not only in ionized regions but also in photodissociation regions (PDRs) large gas-phase abundances of Si have been reported: 30% of the solar abundance in Sharpless 171 (S171; Okada et al. 2003, hereafter OOSD03), 50% in the G333.6-0.2 H ii region (Colgan et al. 1993), 20%–30% in the reflection nebula NGC 7023 (Fuente et al. 2000), and 10% in OMC-1 (Rosenthal et al. 2000). Young Owl et al. (2002) observed nine reflection nebulae and detected [Si ii] 35 μm in two regions with a density range of (0.9–2) × 10^4 cm^−3 and indicated that the intensities of [Si ii] 35 μm in those regions agree with the PDR model. The conversion of the [Si ii] 35 μm intensity to the Si abundance depends on the physical properties, especially the gas density, and thus we need to derive those properties from other line emissions.

In this paper, we report detection of intense [Si ii] 35 μm emission in the ρ Oph reflection nebula based on observations with the Short-Wavelength Spectrometer (SWS; de Graauw et al. 1996) and the Long-Wavelength Spectrometer (LWS; Clegg et al. 1996) on board the Infrared Space Observatory (ISO; Kessler et al. 1996). We discuss the constraint on the Si abundance in the PDR gas, as well as the physical properties of the PDR. Preliminary results have been reported in Tomono et al. (1997). The ρ Oph region is a giant group of molecular clouds that is associated with the Sco OB2 association (Loren 1989). The dense region in the eastern part is known as the ρ Oph main cloud, containing three B-type stars (Yui et al. 1993). The ρ Oph region is well studied by far-infrared forbidden lines (Liseau et al. 1999; Yui et al. 1993), H_2 (Habart et al. 2003), CO (Nozawa et al. 1991; Loren 1989), and [C i] emission (Kamegai et al. 2003). Liseau et al. (1999) made mapping observations of a wide area of the ρ Oph main cloud with the LWS on board the ISO and derived physical properties of the PDR. They suggested that the [O i] 63 μm to 146 μm ratio is too small (<5) to be accounted for by PDR models. Habart et al. (2003) made high spatial resolution observations of H_2 pure rotational and rovibrational transitions in the northern-western part with the SWS. They derived that the ortho-to-para (OTP) ratio is close to unity and suggested that the H_2 formation rate must be high in the warm gas. Here we report one-dimensional raster scan observations with the SWS and LWS, which give us the spatial distribution of [Si ii] 35 μm emission and the correlation with other line emissions from the PDR, and provide a constraint on the Si abundance in the PDR gas.

In addition, we observed a region around σ Sco, a B1 type star located southwest of the ρ Oph region, in order to examine PDR properties and the Si abundance in the same association as ρ Oph. Baart et al. (1980) suggested the presence of a spherical H ii region around σ Sco from the radio continuum emission. Yui et al. (1993) detected extended [C ii] emission with a small peak near σ Sco. De Geus et al. (1990) did not detect the CO line emission around σ Sco, which indicates that the interstellar gas around σ Sco is almost completely photodissociated.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out at 32 positions in the ρ Oph cloud (Fig. 1; Tables 1 and 2), each of which was separated by 3′, or 0.12 pc at the distance of the ρ Oph cloud of 136 pc (Perryman et al. 1997). The position number (p1, etc.) is designated to increase from west to east (toward the molecular cloud; see Fig. 1). The exciting source HD 147889 is located between p13 and p14. A peak of ^13CO is located near p19. For the σ Sco region, one-dimensional raster scan observations were carried out through σ Sco toward the northwest direction, where the [C ii] 158 μm and the IRAS 100 μm continuum emissions show an extended structure (Yui et al. 1993). The observations were carried out at 15 positions (Table 3), each of which was separated by 3′. The position number is designated from northwest to southeast. The exciting source σ Sco is located between p13 and p14 (see Fig. 1).

For both regions, the line profile mode AOT SWS02 was used in the SWS observations to observe [Si ii] 35 μm and the H_2 pure rotational transition S(3) at 9.66 μm in the cycle 1 observation.
### TABLE 1
**Summary of the Forbidden-Line Intensities in the ρ Oph Region**

| No. | R.A.  | Decl.  | $d$ (pc) | [Si ii] 35 μm | [O i] 63 μm | [O i] 146 μm | [C ii] 158 μm |
|-----|-------|--------|----------|----------------|-------------|--------------|---------------|
| 1   | 22 37.15 | 39.83 | 1.50     | <2.73          | <2.15       | <0.34        | 4.12 ± 0.17   |
| 2   | 22 50.33 | 41.17 | 1.39     | <2.72          | <3.07       | <0.42        | 3.54 ± 0.17   |
| 3   | 23 03.52 | 42.45 | 1.27     | <2.82          | <2.73       | <0.36        | 3.26 ± 0.21   |
| 4   | 23 16.70 | 43.66 | 1.15     | <2.40          | <2.81       | <0.31        | 4.50 ± 0.22   |
| 5   | 23 29.88 | 44.80 | 1.03     | <3.10          | <3.24       | <0.39        | 5.15 ± 0.59   |
| 6   | 23 43.97 | 45.86 | 0.91     | <1.77          | <2.29       | <0.39        | 5.42 ± 0.20   |
| 7   | 23 56.24 | 46.85 | 0.79     | <2.53          | <2.24       | <0.34        | 6.07 ± 0.32   |
| 8   | 24 09.43 | 47.77 | 0.67     | <2.47          | <2.93       | <0.51        | 6.11 ± 0.22   |
| 9   | 24 22.60 | 48.62 | 0.56     | <2.87          | <2.96       | <0.27        | 6.80 ± 0.27   |
| 10  | 24 35.79 | 49.41 | 0.44     | <2.54          | <2.86       | <0.53        | 8.02 ± 0.31   |
| 11  | 24 48.97 | 50.11 | 0.32     | <2.28          | <2.97       | <0.59        | 9.30 ± 0.48   |
| 12  | 25 02.15 | 50.75 | 0.20     | <2.63          | <2.63       | <0.34        | 10.66 ± 0.64  |
| 13  | 25 15.34 | 51.31 | 0.08     | 3.61 ± 0.97    | <4.29       | 0.73 ± 0.11  | 11.43 ± 0.63  |
| 14  | 25 28.52 | 51.80 | 0.04     | 5.90 ± 1.06    | 4.05 ± 1.25 | 1.23 ± 0.25  | 17.85 ± 1.63  |
| 15  | 25 41.70 | 52.22 | 0.16     | 7.26 ± 1.07    | 10.05 ± 1.41| 3.25 ± 0.81  | 21.17 ± 1.12  |
| 16  | 25 54.88 | 52.57 | 0.28     | 5.12 ± 0.91    | 12.32 ± 1.31| 1.78 ± 0.32  | 22.21 ± 1.19  |
| 17  | 26 08.06 | 52.85 | 0.39     | 3.28 ± 0.84    | 10.57 ± 1.11| 2.12 ± 0.36  | 20.55 ± 1.13  |
| 18  | 26 21.25 | 53.06 | 0.51     | <3.36          | 6.92 ± 1.14 | 2.37 ± 0.16  | 17.97 ± 0.90  |
| 19  | 26 34.43 | 53.20 | 0.63     | <2.15          | 3.29 ± 0.92 | 0.98 ± 0.22  | 10.21 ± 0.56  |
| 20  | 26 47.62 | 53.26 | 0.75     | <2.87          | 2.64 ± 0.81 | 0.69 ± 0.19  | 8.18 ± 0.42   |
| 21  | 27 00.79 | 53.25 | 0.87     | <3.69          | <2.48       | <0.55        | 7.05 ± 0.40   |
| 22  | 27 13.98 | 53.17 | 0.99     | <2.25          | <3.54       | <0.55        | 6.31 ± 0.32   |
| 23  | 27 27.16 | 53.03 | 1.10     | <3.38          | 2.94 ± 0.82 | <0.79        | 5.77 ± 0.42   |
| 24  | 27 40.34 | 52.80 | 1.22     | <2.29          | <2.30       | <0.34        | 4.72 ± 0.30   |
| 25  | 27 53.53 | 52.51 | 1.34     | <3.60          | <2.84       | <0.48        | 4.08 ± 0.18   |
| 26  | 28 06.71 | 52.14 | 1.46     | <2.14          | <2.51       | <0.47        | 3.74 ± 0.17   |
| 27  | 28 19.89 | 51.71 | 1.58     | <2.63          | <2.52       | <0.43        | 2.74 ± 0.16   |
| 28  | 28 33.07 | 51.20 | 1.70     | <2.96          | <2.21       | <0.36        | 2.48 ± 0.20   |
| 29  | 28 46.25 | 50.62 | 1.82     | <2.65          | <2.41       | <0.29        | 2.38 ± 0.28   |
| 30  | 28 59.44 | 49.97 | 1.94     | <3.05          | <2.52       | <0.38        | 2.81 ± 0.19   |
| 31  | 29 12.62 | 49.25 | 2.05     | <2.34          | <2.68       | <0.26        | 2.51 ± 0.16   |
| 32  | 29 25.81 | 48.45 | 2.17     | <2.04          | <2.22       | <0.27        | 2.31 ± 0.15   |

Note.—Units of right ascension are minutes and seconds, and units of declination are arcseconds.

**a** 16h (J2000.0).

**b** −24°27′ (J2000.0).

**c** Distance from HD 147889.

### TABLE 2
**Summary of the H$_2$ Line Intensities in the ρ Oph Region**

| Position | $v = 1−0$ O(3) | $v = 2−1$ O(3) | $v = 1−0$ O(5) | $v = 2−1$ O(9) | $v = 0−0$ S(3) | $v = 0−0$ S(2) | $v = 0−0$ S(1) | $v = 0−0$ S(0) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 14° × 20″ | 2.80 μm        | 2.97 μm        | 3.23 μm        | 4.91 μm        | 9.66 μm        | 12.3 μm        | 17.0 μm        | 28.2 μm        |
| 14° × 20″ | 14° × 20″      | 14° × 20″      | 14° × 20″      | 14° × 20″      | 14° × 20″      | 14° × 20″      | 14° × 20″      | 14° × 20″      |

Note: The last row of the header indicates the aperture size of the SWS. Ellipses indicate that the observation was not carried out.

**a** The upper limits of the 9.66 μm intensities at the observed positions not listed here are $3.0 \times 10^{-8}$ W m$^{-2}$ s$^{-1}$.

**b** The upper limits of the 9.66 μm intensities at the observed positions not listed here are $3.0 \times 10^{-8}$ W m$^{-2}$ s$^{-1}$. 

a The last row of the header indicates the aperture size of the SWS. Ellipses indicate that the observation was not carried out.
The aperture size was 14" × 20" and 20" × 33", the spectral resolution \( \lambda/\Delta \lambda \) was 1500 and 2000, and the flux calibration accuracy for pointlike sources was 7% and 22% (Leech et al. 2003) for \( \text{H}_2 \, \text{S}(3) \) and \( \text{[Si ii]} \) 35 \( \mu \)m emissions, respectively. Further observations were made from p13 to p20 for other \( \text{H}_2 \) pure rotational and rovibrational transitions in the \( \rho \) Oph region in cycle 2 (Table 2). The aperture size for each transition line observation is not the same (Table 2). The Off-Line Processing (OLP) version 10.1 data obtained from the ISO Archival Data Center were used for the present study. At each raster position one up-and-down grating scan was carried out. The spectra were further processed by using the ISO Spectral Analysis Package (ISAP\(^2\)) in the same manner as for S171 (OOSD03). The conversion factors for extended sources are taken from Leech et al. (2003), which are estimated to be accurate within 10%. The line intensities were derived by Gaussian fits.

The same positions were observed with the LWS full grating scan mode AOT LWS01 to cover the wavelength range from 43 to 197 \( \mu \)m with \( \lambda/\Delta \lambda \sim 100–300 \) (Gry et al. 2003). Four grating scans were carried out for each raster position with the spectral sampling of half the resolution element. The total integration time at a grating position was 2 s. The LWS beam size was 66"–86", depending on the wavelength (Gry et al. 2003). The OLP 10.1 data were used in the present study. We used ISAP for further data processing and derived the line intensities by Gaussian fits. The absolute flux calibration uncertainty is reported to be 10%–20% for point sources and 50% for extended sources (Gry et al. 2003).

### 3. RESULTS AND DISCUSSION

In the \( \rho \) Oph region, we detected two lines, \( \text{H}_2 \, \text{S}(3) \) 9.66 \( \mu \)m and \( \text{[Si ii]} \) 35 \( \mu \)m, in the SWS spectra and three forbidden lines, \( \text{[O i]} \) 63 \( \mu \)m, \( \text{[O i]} \) 146 \( \mu \)m, and \( \text{[C ii]} \) 158 \( \mu \)m, in the LWS spectra for the cycle 1 observations. In cycle 2 we detected three pure rotational lines of \( \text{H}_2 \, \text{S}(2) \) 12.3 \( \mu \)m, \( \text{S}(1) \) 17.0 \( \mu \)m, and \( \text{S}(0) \) 28.2 \( \mu \)m. The results are summarized in Tables 1 and 2. The detected ionic lines arise only from elements with ionization potential less than that of hydrogen (C and Si). The absence of ionization lines, such as \( \text{[N ii]} \) 122 \( \mu \)m or \( \text{[O iv]} \) 88 \( \mu \)m, have been detected, which is consistent with the absence of a radio continuum emission peak around HD 147889 (Baart et al. 1980). The \( \text{[O i]} \) 146 \( \mu \)m line was observed by two adjacent detectors, LW3 and LW4. The line intensities derived from different detectors are in agreement with each other within the estimated uncertainties. We use the weighted mean of the intensities from the two detectors in the following analysis. When the line was detected by only one detector with the other being an upper limit, we adopted the intensity of the detected channel.

The results of the \( \sigma \) Sco region are summarized in Table 3. \( \text{[Si ii]} \) 35 \( \mu \)m and \( \text{H}_2 \, 9.66 \mu \)m have not been detected at any positions in the SWS spectra. In the LWS spectra we detected three forbidden lines, \( \text{[O i]} \) 63 \( \mu \)m, \( \text{[N ii]} \) 122 \( \mu \)m, and \( \text{[C ii]} \) 158 \( \mu \)m. The \( \text{[N ii]} \) 122 \( \mu \)m emission traces the low-density ionized gas, and the detection of this line is consistent with the presence of the radio continuum emission peak (Baart et al. 1980). On the other hand, the lack of emission lines from highly ionized ions such as \( \text{[O iii]} \) and \( \text{[N iii]} \) is consistent with the late spectral type (B1) of the exciting star.

The errors in the line intensities include both the fitting errors and the statistical errors of the baseline. Uncertainties in the absolute flux are not included in the errors in Tables 1–3. We treat line emission less than 3 times the uncertainty (<3 \( \sigma \)) as a non-detection and give 3 \( \sigma \) as the upper limit. For each region, the lines not listed in Tables 1–3 are not detected at all the observed positions and only upper limits are derived as \( \text{[O iii]} \) 52 \( \mu \)m < 2.7 \times 10^{-7}, \( \text{[N ii]} \) 57 \( \mu \)m < 2.0 \times 10^{-7}, \( \text{[O ii]} \) 88 \( \mu \)m < 6.9 \times 10^{-8}, and \( \text{[N ii]} \) 122 \( \mu \)m < 3.6 \times 10^{-8} W m^{-2} sr^{-1} for the \( \rho \) Oph region and \( \text{H}_2 \, 9.66 \mu \)m < 3.6 \times 10^{-8} \( \mu \)m. The results are consistent with the late spectral type (B1) of the exciting star.

### Table 3

#### SUMMARY OF THE LINE INTENSITIES IN THE \( \sigma \) SCO REGION

| No. | R.A.\(^{a}\) | Decl.\(^{b}\) | \( d \)^{c} (pc) | \( \text{[O i]} \ 63 \mu \text{m} \) | \( \text{[N ii]} \ 122 \mu \text{m} \) | \( \text{[C ii]} \ 158 \mu \text{m} \) |
|-----|-------------|-----------|----------------|-----------------|-----------------|-----------------|
| 1   | 19 13.73    | 09 05.90  | 1.55           | 1.14 ± 0.36     | <0.23           | 2.14 ± 0.21     |
| 2   | 19 23.10    | 11 13.20  | 1.43           | 0.82 ± 0.27     | <0.18           | 2.68 ± 0.15     |
| 3   | 19 32.48    | 13 20.50  | 1.30           | <1.00           | <0.21           | 2.82 ± 0.21     |
| 4   | 19 41.87    | 15 27.70  | 1.18           | <1.36           | <0.27           | 3.74 ± 0.16     |
| 5   | 19 51.26    | 17 34.90  | 1.05           | 1.73 ± 0.29     | <0.42           | 4.37 ± 0.20     |
| 6   | 20 00.65    | 19 42.10  | 0.93           | 1.67 ± 0.36     | <0.28           | 4.45 ± 0.18     |
| 7   | 20 10.05    | 21 49.30  | 0.81           | 1.14 ± 0.36     | 0.34 ± 0.09     | 4.71 ± 0.23     |
| 8   | 20 19.46    | 23 56.40  | 0.68           | <1.23           | <0.59           | 4.53 ± 0.19     |
| 9   | 20 28.87    | 26 03.40  | 0.56           | <1.07           | 0.44 ± 0.14     | 4.23 ± 0.22     |
| 10  | 20 38.29    | 28 10.50  | 0.43           | <1.32           | 0.40 ± 0.11     | 4.44 ± 0.19     |
| 11  | 20 47.71    | 30 17.40  | 0.31           | <1.04           | <0.27           | 3.47 ± 0.13     |
| 12  | 20 57.14    | 32 24.40  | 0.19           | <1.44           | <0.25           | 3.29 ± 0.17     |
| 13  | 20 66.58    | 34 31.30  | 0.06           | <1.47           | 0.34 ± 0.08     | 2.46 ± 0.17     |
| 14  | 21 16.02    | 36 38.20  | 0.06           | <1.22           | <0.29           | 2.57 ± 0.10     |
| 15  | 21 25.66    | 38 45.00  | 0.19           | <1.06           | <0.30           | 2.65 ± 0.10     |

Note.—Units of right ascension are minutes and seconds, and units of declination are arcminutes and arcseconds.

\(^{a}\) 16h (J2000.0).

\(^{b}\) –25 (J2000.0).

\(^{c}\) Distance from \( \sigma \) Sco.

\(^2\) The ISO Spectral Analysis Package (ISAP) is a joint development by the LWS and SWS Instrument Teams and Data Centers. Contributing institutes are CESR, IAS, IPAC, MPE, RAL, and SRON.
Figures 2 and 3 show the spatial distributions of the line intensities for the ρ Oph and σ Sco regions, respectively. For the ρ Oph region, the line emissions other than [C II] 158 μm are detected only at p13–p20 and p23, near the surface regions of the molecular clouds. The [C II] 158 μm emission is detected at all the observed positions and shows a peak at p15. This is consistent with the result of Yui et al. (1993), who reported an extended distribution of the [C II] emission.

3.1. PDR Properties

We estimate the properties of the PDR from the observed lines and continuum emission using the PDR model by Kaufman et al. (1999). The major model parameters are the gas density, n, and the UV radiation field strength, \( G_0 \), in units of the solar neighborhood value (Habing 1968; 1.6 × 10^{-6} \text{ W m}^{-2}). The model gives integrated line intensities seen in the face-on view. In the following, we discuss only the results of the positions where all three types of emission, [O I] 63 μm, 146 μm, and [C II] 158 μm, are detected (p14–p20). Although no appreciable amount of the ionized gas has been detected in the ρ Oph region, part of the [C II] 158 μm may come from the undetected ionized gas. From 2.3 GHz radio continuum observations ( emission measure = 176 pc cm^{-6}; Baart et al. 1980), we estimate the contribution of the [C II] 158 μm emission from the ionized gas to be less than 6% assuming the low-density limit condition and the interstellar abundance (Savage & Sembach 1996). This fraction is smaller than the uncertainty in the observed intensity. A possible contribution from the ionized gas thus will not affect the following discussion on the PDR properties within the observational uncertainties. Comparison between the observation and the PDR model can be made less ambiguously for the ρ Oph region than for H II regions, such as S171 (OOSD3).

The ratio of the observed [O I] 63 μm/[O I] 146 μm is too small (3–7) compared to PDR models of any parameter range, and no PDR models can account for the observed line intensities of [O I] 63 μm, 146 μm, and [C II] 158 μm consistently. The small ratio of [O I] 63 μm/[O I] 146 μm in the ρ Oph region has been reported by Liseau et al. (1999) and is attributed to the optically thick emission of [O I] 63 μm (Caux et al. 1999). To derive the physical properties of the PDR and quantitatively explain the discrepancy between the observed line intensities and the prediction from the PDR model by Kaufman et al. (1999), we adopt a simple model that was applied for S171 (OOSD3). [O I] 63 μm is optically thick, [C II] 158 μm is marginally thick (\( \tau \sim 1 \)), and [O I] 146 μm and the far-infrared continuum emission are optically thin in a PDR (Kaufman et al. 1999). OOSD3 suggest that overlapping PDR clouds along the line of sight attenuate the former two line emissions, while the intensities of the latter two will be a simple summation of those from each PDR cloud. Therefore, we use the [O I] 146 μm to the total far-infrared intensity (FIR) ratio and \( G_0 \) as input parameters to estimate the density and the surface temperature using the PDR model (Figs. 4a–4c). We fit the continuum
emission of the LWS spectra with a graybody radiation of the $\lambda^{-1}$ emissivity and estimate $G_0$ by assuming $(\tau_{abs})/\tau_{100} = 700$ and $f = 0.5$, where $(\tau_{abs})$ is the weighted mean of the absorption optical depth over the mean intensity from the heating source, $\tau_{100}$ is the optical depth at 100 $\mu$m, and $f$ is the ratio of the energy between 6 and 13.6 eV to the total luminosity for the spectrum of HD 147889 of a blackbody of $T_{eff} = 20,300$ K (see OOSD03 for details). Models with these parameters predict [O $\scriptstyle{I}$] 63 $\mu$m and [C $\scriptstyle{II}$] 158 $\mu$m emissions stronger than those observed. This can be explained by taking into account the overlapping factor $Z$ defined as

$$Z = \frac{\text{FIR}(\text{obs})}{\text{FIR}(\text{model})},$$

(1)

where FIR(model) = 1.6 $\times$ 10^{-6}$G_0/4\pi f$ W m^{-2} sr^{-1} with the assumption that all the incident radiation is absorbed and converted into far-infrared emission. For $Z < 1$, $Z$ is equal to the beam filling factor, whereas it indicates the degree of overlapping of clouds for $Z > 1$, since the far-infrared emission is optically thin. Figure 4d shows the estimated Z with the errors including the absolute flux uncertainty of the LWS. At the positions of p14–p20, Z is larger than unity, suggesting that the effect of overlapping clouds is significant. We assume that the size of a cloud is smaller than the beam ($\leq 0.06$ pc), and the column density for [O $\scriptstyle{I}$] 63 $\mu$m in a cloud is sufficiently large ($N_{H_{1+H_{2}}} \gtrsim 5 \times 10^{21}$ cm$^{-2}$). To examine the effect of the overlapping on the observed intensity we simply assume that $N$ identical clouds overlap on the line of sight and attenuate the line emissions. Then the observed [O $\scriptstyle{I}$] 63 $\mu$m and [C $\scriptstyle{II}$] 158 $\mu$m should be attenuated by a factor of

$$\frac{\sum_{j=0}^{N-1} e^{-j\tau}}{N} = \frac{1 - e^{-N\tau}}{N(1 - e^{-\tau})},$$

(2)

where the number of clouds $N$ can be substituted by $Z$ (OOSD03). We assume $\tau = \infty$ for [O $\scriptstyle{I}$] 63 $\mu$m and $\tau = 1$ for [C $\scriptstyle{II}$] 158 $\mu$m. The corrected [O $\scriptstyle{I}$] 63 $\mu$m and [C $\scriptstyle{II}$] 158 $\mu$m intensities, together with the observed [O $\scriptstyle{I}$] 146 $\mu$m and the far-infrared emissions, can be accounted for by the PDR model of $G_0$ and $n$ of Figures 4a and 4b within 1 $\sigma$ except for p14 and p15, where the model prediction of [O $\scriptstyle{I}$] 63 $\mu$m is still slightly larger than the observed intensities (Figs. 4e and 4f). In Figures 4e and 4f, the errors in the model prediction include the uncertainty in the derived parameters ($G_0$ and $n$), whereas those in the observed intensities include the uncertainties in the original intensity (Table 1) and those in $Z$ (Fig. 4d). The derived distributions of $G_0$, $n$, and the surface temperature are compatible with the CO observations and the location of the exciting source. In the present estimate, we assume that the cloud density is the same among PDRs along the line of sight to simplify the calculation and the derived density represents a mean value of the true distribution. The agreement of the model prediction with the corrected line intensities at five positions supports the interpretation of overlapping PDR clouds for the line intensities in a semiquantitative way.

For all 15 observed positions in the $\sigma$ Sco region we find $Z < 1$, which indicates that the [O $\scriptstyle{I}$] 63 $\mu$m emission is unlikely to be attenuated by overlapping PDR clouds. Therefore, we use the [O $\scriptstyle{I}$] 63 $\mu$m emission instead of the [O $\scriptstyle{I}$] 146 $\mu$m emission to derive the PDR properties (Figs. 5a–5c). There is an H $\alpha$ region associated with $\sigma$ Sco, and the [C $\scriptstyle{II}$] 158 $\mu$m emission originates both from the ionized and the PDR gas. The [C $\scriptstyle{II}$] 158 $\mu$m intensity predicted by the PDR model is smaller than those observed (Fig. 5d). The excess intensity is attributed to the emission from the ionized gas. The contribution from the ionized gas is 30%–80% at three positions closest to the excitation star (p5, p6, and p7). Yui et al. (1993) suggested that the [C $\scriptstyle{II}$] 158 $\mu$m emission comes from the neutral gas adjacent to the H $\alpha$ region based on the poor correlation between the radio continuum and the [C $\scriptstyle{II}$] 158 $\mu$m emission. The present results indicate that a nonnegligible fraction of the [C $\scriptstyle{II}$] 158 $\mu$m emission comes from the ionized gas in the $\sigma$ Sco region.

### 3.2. Silicon Abundance in the PDR

In the $\rho$ Oph region, we have detected strong [Si $\scriptstyle{II}$] 35 $\mu$m emission. With the gas density $\sim 10^{5}$ cm$^{-3}$ and $G_0 \sim 10^4$, the PDR model (Hollenbach et al. 1991) predicts the [Si $\scriptstyle{II}$] 35 $\mu$m to [O $\scriptstyle{I}$] 146 $\mu$m intensity ratio to be $\sim 0.4$, while the observation shows a ratio of $\sim 2$–4 (Fig. 6). The abundance of Si is assumed to be 2.3% of the solar abundance in the model. If we attribute the difference to the abundance or the degree of depletion of Si, it suggests that 10%–20% of the solar abundance of Si must reside in the gas phase in the PDR of $\rho$ Oph. The optical depth of [Si $\scriptstyle{II}$] 35 $\mu$m in a typical PDR is about 0.1, and thus the overlapping...
effect is negligible. The [Si II] 35 μm and [O I] 146 μm transitions have similar excitation energies (413 and 327 K, respectively), and both transitions, as well as [O I] 63 μm, have critical densities higher than 10^5 cm^-3 with the collision partner of atomic hydrogen. The calculation for an isothermal cloud with a uniform density with the optically thin condition shows that the [Si II] 35 μm to [O I] 146 μm ratio is not dependent on the gas density for n ≤ 10^4 cm^-3 and not sensitive to the gas temperature for T ≥ 300 K. In fact, PDR model calculations suggest that the ratio changes by only 10% for n < 10^4 cm^-3 and 10^2 ≤ G0 ≤ 10^3 (Wolfire et al. 1990). Meixner & Tielens (1993) showed that clumpy PDRs can increase the [Si II] 35 μm to [O I] 146 μm intensity ratio by a factor of 1.5. Clumpiness alone cannot fully account for the observed large ratio. Liseau et al. (1999) showed that the density of the PDR in the ρ Oph main cloud is (1–3) × 10^4 cm^-3, which is larger by 1 order of magnitude than the present result. The discrepancy comes from the different PDR models employed: the model by Kaufman et al. (1999) takes account of the heating by polycyclic aromatic hydrocarbons that produces strong [O I] emissions at low densities. The [Si II] 35 μm to [O I] 146 μm intensity ratio is not sensitive to the density as mentioned above, and thus the large ratio must be attributed to a large Si abundance irrespective of the assumed density. As with the [C II] 158 μm emission, the [Si II] 35 μm emission can originate from the ionized gas. We estimate from the radio continuum observation (Baart et al. 1980) that only 30% of the observed [Si II] 35 μm emission can be attributed to the ionized gas even if the gaseous Si abundance is solar. Therefore, most [Si II] 35 μm emission should come from the PDR and the possible contribution from the ionized gas will not affect the above discussion on the large gas-phase abundance of Si in the PDR.

The column density of Si included in dust grains can be estimated from the dust model and τ_{100}, which is derived from the graybody fit of the continuum spectra. We use the dust model by Draine & Lee (1984) with the assumptions of the density of dust grains of 3.3 g cm^-3 and the mean molecular weight of 100–200 for olivine and pyroxene. On the other hand, we can estimate the column density of Si^{+} from the [Si II] 35 μm intensity, the gas density, and the gas temperature. We use the density and the surface temperature derived from the PDR model in § 3.1 in the following discussion. For a given intensity, the column density decreases with temperature, and thus a highest likely temperature gives a lower limit of the column density. Figure 7 plots the column density of Si in gas against that in dust. It indicates that the relative fraction of Si in the gas and dust phases is in agreement with the result from the [Si II] 35 μm/[O I] 146 μm ratio. Note that this estimate is independent of the assumed solar abundance. If the density is higher by 1 order of magnitude as suggested by Liseau et al. (1999), we obtain a lower column density of Si in the gas phase by 1 order of magnitude. Then [Si II] 35 μm/[O I] 146 μm is estimated to be lower than observed. The gas-phase abundance of Si estimated from [Si II] 35 μm and τ_{100} supports the present estimate of the gas density (~10^3 cm^-3), although we cannot exclude the higher density because of large uncertainties.

The temperature of H2-emitting gas can be estimated from the ratio of the H2 line emissions. Assuming the Boltzmann distribution at low-J transitions and the homogeneous distribution of the emissions in the aperture, we derive the temperature of ortho–H2 to be 298 ± 12, 315 ± 20, 310 ± 9, and 307 ± 8 K at p15–p18 in the ρ Oph region, respectively, from the line intensities of 9.66 and 17.0 μm. Although the aperture size for each line is not the same (Table 2), similar temperatures derived at four positions suggest that the differences in the aperture size do not significantly affect the estimates. At p18, we also detect two lines from para-H2 at 12.3 and 28.2 μm, and derive the temperature as 260 ± 21 K, which gives a temperature similar to that from ortho-H2 lines. The temperature of the H2-emitting gas is in a range similar to that of the surface temperature. If we use the temperature of H2 emission to estimate the column density of gaseous Si^{+}, the conclusion remains unchanged.

According to theoretical investigations, dust grains in interstellar space are destroyed on a timescale of (2–4) × 10^8 yr by supernova shock waves (Jones et al. 1994, 1996). However, the gas densities of the PDR are several hundreds to several thousands of cubic centimeters, and a shock cannot penetrate these regions easily. Some fraction of Si may reside in volatile forms in dust grains that can be easily destroyed. Several forms of Si in dust grains are proposed to explain the fact that on the order of 10% of Si atoms easily return to the gas phase: a volatile component with a binding energy of E_b ≈ 1–2 eV (Tielens 1998), a mantle being photodesorbed by UV photons (Walmsley et al. 1999), and organometallic complexes (Klotz et al. 1995; Marty et al. 1994). The present study suggests that about 10% of Si atoms may reside in some of these forms in dust grains that are relatively easily ejected to the gas phase by UV photons. The recycling, as well as the composition, of dust grains in interstellar space should be reexamined based on further systematic observations of variations in different environments and other dust component elements.

In the σ Sco region, the upper limit of the [Si II] 35 μm to [N II] 122 μm intensity ratio indicates that the Si abundance in the ionized gas should be lower than 100% of the solar abundance, and no useful constraint on the abundance of Si in the gas phase is obtained.

4. SUMMARY

We observed the ρ Oph main cloud and the σ Sco region with SWS and LWS on board the ISO. We have detected eight lines, [Si II] 35 μm, H2 pure rotational transition lines S(0) to S(3), [O I] 63 μm, 146 μm, and [C II] 158 μm, in the ρ Oph region and three fine-structure lines, [O I] 63 μm, [N II] 122 μm, and [C II] 158 μm, in the σ Sco region.

In the ρ Oph region, the observed [O I] 146 μm emission is too weak and the [O I] 63 μm and [C II] 158 μm emissions too strong compared to PDR models. As has been proposed for Si171
(OOSD03), we adopt a simple model of overlapping PDR clouds along the line of sight that attenuate the [O i] 63 μm and [C ii] 158 μm. We show that this model accounts for the intensities of the [O i] 63 μm, 146 μm, [C ii] 158 μm, and the continuum emission at the same time. Because of the absence of the H II region in ρ Oph, the present analysis supports the validity of the overlapping model with less ambiguity. The gas density varies over 250–2500 cm\(^{-3}\) and the surface temperature \(T \sim 100–400\) K for the ρ Oph region. In the σ Sco region, the overlapping effect is negligible and we derive physical conditions from the [O i] 63 μm emission. Comparison of the model prediction indicates that 30%–80% of the [C ii] 158 μm emission comes from the ionized gas in the vicinity of σ Sco.

The [Si ii] 35 μm emission was observed quite strongly in the ρ Oph region. With the derived PDR properties we discuss the large Si abundance in the PDR gas in the ρ Oph region. The observed ratio of [Si ii] 35 μm to [O i] 146 μm indicates the Si abundance in the PDR gas to be 10%–20% of solar, suggesting the dust destruction taking place in the PDR. This result is supported by comparison of the [Si ii] 35 μm intensity with the continuum emission for \(n \sim 10^3\) cm\(^{-3}\). The present results strongly suggest that some fraction of Si atoms must be included in volatile forms in dust grains that are relatively easily destroyed. The present observation indicates the importance of the [Si ii] 35 μm line in future observations to investigate the dust destruction and the composition of dust grains.

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