Si and Fe depletion in Galactic star-forming regions observed by the *Spitzer Space Telescope*

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ABSTRACT

We report the results of the mid-infrared spectroscopy of 14 Galactic star-forming regions with the high-resolution modules of the Infrared Spectrograph (IRS) on board the *Spitzer Space Telescope*. We detected [Si II] 35 μm, [Fe II] 26 μm, and [Fe III] 23 μm as well as [S III] 33 μm and H_2 S(0) 28 μm emission lines. Based on photodissociation and H II region models the gas-phase Si and Fe abundance are suggested to be 3–100% and $<$ 22% of the solar abundance, respectively. Since the [Fe II] 26 μm and [Fe III] 23 μm emissions are weak, the high sensitivity of the IRS enables to derive the gas-phase Fe abundance widely in star-forming regions. The derived gas-phase Si abundance is much larger than that in cool interstellar clouds and that of Fe. The present study indicates that 3–100% of Si atoms and $<$ 22% of Fe atoms are included in dust grains which are destroyed easily in H II regions, probably by the UV radiation. We discuss possible mechanisms to account for the observed trend; mantles which are photodesorbed by UV photons, organometallic complexes, or small grains.

Subject headings: Infrared:ISM – ISM:abundances – dust – H II regions

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1. Introduction

One of the methods to probe chemical compositions of interstellar dust grains is to examine the gas-phase abundance of a certain element and attribute its deficiency against the reference abundance (i.e. depletion) to those contained in dust grains. Since the gas-phase emission or absorption lines are relatively easy to observe and interpret, this method can be applied for large samples. The depletion pattern in diffuse interstellar matter (ISM) has been studied on the basis of ultraviolet (UV) absorption lines (Savage & Sembach 1996; Jenkins 2004). Depletion in active star-forming regions, where the density is much higher than in diffuse clouds ($n_{\rm H} \sim 10$–$10^6{\rm cm}^{-3}$), has been studied by infrared line emissions with the *Kuiper Airborne Observatory* (*KAO*) and the *Infrared Space Observatory* (*ISO*; Kessler et al. 1996). The large gas-phase Si abundance has been suggested by the intense [Si II] 35 μm emission in several regions including star-forming regions (Stolovy et al. 1995; Okada et al. 2003; Mizutani et al. 2004). Not only in ionized regions but also in photodissociation regions (PDRs) large gas-phase Si abundances of 10–50% of solar have been reported in star-forming regions (Colgan et al. 1993; Fuente et al. 2000; Rosenthal et al. 2000; Okada et al. 2006), whereas Young Owl et al. (2002) indicated that the intensities of [Si II] 35 μm in two reflection nebulae agree with the interstellar gas phase abundance (a few percent of solar).

At visual wavelengths, there are few studies of the gas-phase abundance of highly depleted elements in H II regions (Rodríguez 2002). Since the [Fe II] 26 μm and [Fe III] 23 μm lines are weak, only a few detections of these lines have been so far reported and little constraint on the gaseous Fe abundance has been imposed before the *Spitzer Space Telescope* (Werner et al. 2004) in infrared. In this paper, we report the depletion pattern of Fe as well as Si in Galactic star-forming regions observed with the Infrared Spectrograph (IRS; Houck et al. 2004) on board *Spitzer*.

2. Observations and Data Reduction

We have observed two groups of targets. As group (a) targets, we have selected four star-forming regions where far-infrared spectroscopic observations have been made by *ISO* or *KAO* at more than two positions, and the [N II] 122 μm or 205 μm (if in the ionized region) and [O I] 146 μm or 63 μm emissions have been obtained, and the properties of the PDR gas have been derived. We examine correlations among lines detected by the IRS with them, deriving the abundance of Si^+ and Fe^+ relative to N^+ or O^0 in H II regions and/or PDRs. To take account of the difference in the aperture size between the IRS ($11.1'' \times 22.3''$ for the whole slit) and the *ISO*/LWS ($66.4''$–$87.0''$) or *KAO* ($45''$–$60''$), we observed 4 positions

(2 × 2 mapping) with the IRS within the aperture of the *ISO* or *KAO*. Group (b) targets have been selected from Conti & Crowther (2004) of a catalog of giant Galactic H II regions in the Galactic plane with a Lyman continuum photon number $N(\mathrm{Lyc}) \geq 10^{50}$ photon s^{-1}.

The observations were performed in the cycle 2 general observer program (ID: 20612) of *Spitzer*. All targets were observed with the LH module of the IRS, which provided spectra of $\lambda/\Delta\lambda \sim 600$ in 18.7–37.2 μm. Table 1 shows the summary of the observed targets. See Okada et al. (2008) for details of the procedure of data reduction.

Table 1: Summary of the observed targets.

	Target	N_p[a]	$N(\mathrm{Lyc})$[b] [sec $^{-1}$]	Electron density [cm^{-3}]
group a	S171	(2 × 2 map) ×6	8.94×10^{48}	< 70
	G333.6-0.2	(2 × 2 map) ×4	2.69×10^{50}	< 210
	σ Sco	(2 × 2 map) ×3	3.5×10^{45}	< 20
	NGC 1977	(2 × 2 map) ×3	4×10^{46}	102
group b	G0.572-0.628	8	1.1×10^{50}	117
	G3.270-0.101	8	3.0×10^{50}	31
	G4.412+0.118	8	3.6×10^{50}	38
	G8.137+0.228	8	3.0×10^{50}	160
	G32.797+0.192	6	1.1×10^{50}	102
	G48.930-0.286	8	1.1×10^{50}	117
	G79.293+1.296	8	1.4×10^{50}	110
	G347.611+0.2	8	2.8×10^{50}	57
	G351.467-0.462	6	1.5×10^{50}	64
	G359.429-0.090	8	2.9×10^{50}	93

[a] The number of the observed position.

[b] The number of Lyman continuum photon.

3. Results

[Si II] 35 μm emission is detected at all the positions, and [Fe II] 26 μm and [Fe III] 23 μm emissions are detected at more than half of the mapping positions of most targets. [S III] 33 μm emission is detected at all the positions except for NGC 1977, and $\mathrm{H_2}$ S(0) 28 μm emission is also detected at most targets. [Si II] 35 μm and [Fe II] 26 μm can originate both from the ionized and PDR gas since the first ionization potentials of Si and Fe are less than 13.6 eV. On the other hand, [Fe III] 23 μm as well as [S III] 33 μm and [N II] 122 μm stem only from the ionized gas thus we use those lines to discuss the gas-phase abundance in the ionized gas. These lines are collisionally excited by electrons. The $\mathrm{H_2}$ 28 μm emission as well as [O I] 63 μm and 146 μm traces the PDR gas.

In the following, we describe the abundance ratio of two ions against the solar abundance by Asplund et al. (2005) as $(Fe^{2+}/S^{2+})_{as} \equiv (Fe^{2+}/S^{2+})/(Fe^{2+}/S^{2+})_{\odot}$, where "as" means "against solar". Since S and N are considered to be little depleted (Savage & Sembach 1996), we use line ratios against [S III] or [N II] lines to discuss the depletion pattern of Si and Fe. For the PDR gas, we compare the observed line ratios with those of PDR models by Kaufman et al. (2006) and simply attribute the discrepancy to the abundance ratios. We estimate the abundance ratio from comparison of the observed line ratios with those of the models by simple scaling.

3.1. Si^+ and Fe^+ abundance against N^+ and O^0

For group (a) targets, we examine Si^+ and Fe^+ abundance against N^+ and O^0 with previous observations by *ISO* or *KAO*. In NGC 1977, the [Ar III] 22 μm, [Fe III] 23 μm, and [S III] 33 μm emissions, which come from the ionized gas, were not detected. This is consistent with that all the observed positions are located outside the ionization front on the edge-on structure. Thus [Si II] 35 μm and [Fe II] 26 μm emissions are considered to come from the PDR. In Sharpless 171 (S171), G333.6-0.2, and σ Sco, these emissions can originate both ionized and PDR gas. See Okada et al. (2008) for detail discussion of each region.

In S171, the [Si II] 35 μm and [N II] 122 μm emissions observed with *ISO* show a good correlation, suggesting that most [Si II] 35 μm emission comes from the ionized gas except for positions near the molecular cloud, where a significant contribution from the PDR is indicated (Okada et al. 2003). Okada et al. (2003) suggested that $(Si^+/N^+)_{as} = 0.3 \pm 0.1$ assuming that the ionized gas for the origin of the [Si II] 35 μm, which is $(Si^+/N^+)_{as} = 0.22 \pm 0.07$ when we use the solar abundance by Asplund et al. (2005). With assuming that all the [Fe II] 26 μm comes from the ionized gas, the ratio to [N II] 122 μm observed by *ISO* indicates $(Fe^+/N^+)_{as} = 0.005$–0.05. In G333.6-0.2, the good correlation between [Si II] 35 μm and [S III] 33 μm indicates that the major fraction of the [Si II] 35 μm emission comes from the ionized gas. We use the [N II] emission observed by *KAO* (Simpson et al. 2004) and derive $(Si^+/N^+)_{as} = 0.20$ (± 0.05), 0.31 (± 0.10), and 0.13 ($+0.83/-0.06$) for three mapping positions. The derived $(Si^+/N^+)_{as}$ is in the same order of magnitude as in S171. If we assume that all the [Fe II] 26 μm emission comes from the ionized gas, the ratio to [N II] emission observed by *KAO* indicates $(Fe^+/N^+)_{as} < 0.05$. In the σ Sco region, the [Si II] 35 μm and [Fe II] 26 μm emission was detected for the first time. If all the [Si II] 35 μm and [Fe II] 26 μm emission comes from the ionized gas, the ratio to [N II] 122 μm observed by *ISO* indicates $(Si^+/N^+)_{as} \sim 0.08$–$0.25$ and $(Fe^+/N^+)_{as} \sim 0.03$–$0.06$.

On the other hand, it is also indicated that the contribution from the PDR should not be negligible in these regions. In S171, Okada et al. (2003) suggested a significant contribution from the PDR in positions near the molecular cloud. If we assume that all the [Si II] 35 μm and [Fe II] 26 μm emission comes from the PDR gas, we estimate $(Si^+)_{as}$ and $(Fe^+)_{as}$ using [O I] 146 μm and PDR properties derived in Okada et al. (2003) as 0.4–0.6 and 0.03–0.15, respectively. In G333.6-0.2, the [Si II] 35 μm/[N II] 122 μm ratio in the center (Colgan et al. 1993) indicates the Si abundance of over 100% solar and thus part of [Si II] 35 μm emission should come from the PDR. Since [O I] lines are observed only at the center of G333.6-0.2 and [Si II] 35 μm/H_2 28 μm and [Fe II] 26 μm/H_2 28 μm depend largely on PDR properties, no significant constraints are imposed on $(Si^+)_{as}$ and $(Fe^+)_{as}$. In σ Sco, the [Si II] 35 μm/H_2 28 μm and [Fe II] 26 μm/H_2 28 μm indicates $(Si^+)_{as}$ and $(Fe^+)_{as}$ to be 0.2–1.6 and 0.03–0.22, respectively, if all the [Si II] 35 μm and [Fe II] 26 μm emissions come from the PDR gas with the properties derived in Okada et al. (2006).

In NGC 1977, we reanalyze data of [O I] 63 μm, 146 μm, [C II] 158 μm and [Si II] 35 μm with *KAO* reported by Young Owl et al. (2002), together with H_2 28 μm detected by the IRS using the latest PDR model by Kaufman et al. (2006). If we assume that [O I] 63 μm emission is intrinsically stronger than the observed intensity by a factor of 2.5, the line ratios between [O I] 63 μm, 146 μm, and [C II] 158 μm are consistent with PDR gas with the radiation field $G_0 \sim 5000$ and the gas density $n \sim 10^3 \mathrm{cm}^{-3}$. Then $(Si^+)_{as}$ should be $\sim$ 0.16, 3 times larger than Si abundance assumed in the PDR model to account for all the line ratios. In other observed positions in NGC 1977, [Si II] 35 μm/H_2 28 μm is lower, which indicates lower values of G_0 and/or n, or $(Si^+)_{as} \sim 0.1$. The observed [Si II] 35 μm/[Fe II] 26 μm indicates $(Fe^+)_{as} =\sim$ 0.02–0.04, 4–8 times larger than Fe abundance in the model if $(Si^+)_{as} = 0.16$.

3.2. $(Fe^+/Si^+)_{as}$, $(Si^+/S^{2+})_{as}$, and $(Fe^{2+}/S^{2+})_{as}$

For all the observed targets, we derive $(Fe^+/Si^+)_{as}$, $(Si^+/S^{2+})_{as}$, and $(Fe^{2+}/S^{2+})_{as}$ by assuming that [Fe II] 26 μm and [Si II] 35 μm emissions come from the ionized gas as well as [Fe III] 23 μm and [S III] 33 μm, and that the abundance is constant within one star-forming region. Those are plotted in Fig. 1. In contrast to Si^+, $(Fe^{2+}/S^{2+})_{as}$ is below 0.1 even taking account of errors in all the 10 regions.

4. Discussion

The analysis in the previous section derives the ionic abundance ratio as $(Fe^+/Si^+)_{as}$ = 0.005–0.38, $(Si^+/S^{2+})_{as}$ = 0.03–1.7, $(Si^+/N^+)_{as}$ = 0.08–0.4, $(Fe^{2+}/S^{2+})_{as}$ = 0.002–0.08, and

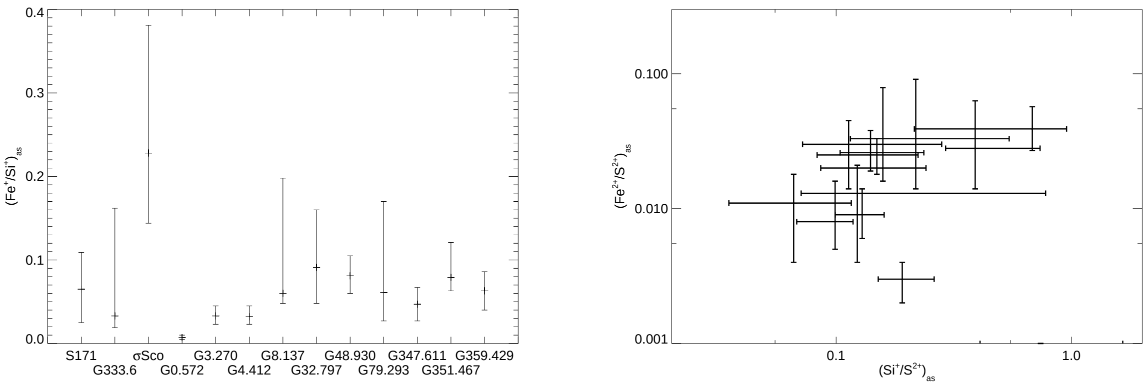

Fig. 1.— $(Fe^+/Si^+)_{as}$ with assuming that [Fe II] 26 μm and [Si II] 35 μm emissions are from the ionized gas (left) and $(Fe^{2+}/S^{2+})_{as}$ against $(Si^+/S^{2+})_{as}$ (right).

$(Fe^+/N^+)_{as} = 0.005$–0.06 in the ionized gas, and $(Si^+)_{as} = 0.16$–1.6 and $(Fe^+)_{as} = 0.02$–0.22 in the PDR gas. It is clearly shown that Fe is highly depleted than Si. The gas-phase Si abundance indicated by $(Si^+/S^{2+})_{as}$ and $(Si^+/N^+)_{as}$ is 3%–100% of the solar abundance in the ionized gas in a wide range of the exciting stars (Table 1). Together with the result of Okada et al. (2003, 2006), several PDRs also have similar gas-phase Si abundance. On the other hand, the gas-phase Fe abundance indicated by $(Fe^{2+}/S^{2+})_{as}$ and $(Fe^+/N^+)_{as}$ is $< 8\%$ of the solar abundance in all the observed regions (Fig. 1). From UV observations, the gas-phase abundance of Si and Fe in cool interstellar clouds are 5% and 0.5% solar, and those in warm interstellar clouds are 30% and 6% solar (Savage & Sembach 1996). In diffuse interstellar clouds probed by UV observations, shock waves by supernovae destroy dust grains. The gas-phase abundance of several elements including Si and Fe shows a trend to increase with the velocity of the clouds, indicating that shocks that accelerate clouds may be a dominant process for dust destruction (Fitzpatrick 1996; Cowie 1978). The gas-phase Si and Fe abundance in star-forming regions discussed in the present paper is in a range similar to that of warm interstellar clouds. However, dust grains in star-forming regions should originate from dense cool clouds, where Si and Fe are highly depleted, and they are processed by UV radiation or stellar winds from newly born massive stars in a different way from grains in warm interstellar clouds.

It is generally accepted that interstellar dust grains consist of amorphous silicates and some form of carbonaceous materials (Draine 2003). Si, Mg and Fe can be major constituents of silicate, but UV observations indicate that they show different depletion patterns; Si atoms return to the gas phase most easily, Mg is depleted more than or similarly to Si, and Fe atoms tend to insistently remain in dust grains (Sofia et al. 1994; Fitzpatrick 1996; Jones 2000; Cartledge et al. 2006). These indicate that silicates contain primarily Mg and most or all Fe atoms are in other components of dust such as metal or oxides. Although the trend that Si atoms return to the gas phase more easily than Fe is the same in star-forming regions discussed in the present paper as in diffuse ISM, silicate should survive generally in the ionized regions since it has a large binding energy of $\sim$ 5 eV (Tielens 1998). The present study indicates that 3–100% of Si atoms and $<$ 22% of Fe atoms are included in dust grains which are destroyed easily in H II regions, probably by the UV radiation. The presence of mantles which release Si atoms into the gas phase by photodesorption by UV photons (Walmsley et al. 1999) or organometallic complexes such as PAH cluster (Marty et al. 1994; Klotz et al. 1995) is suggested. Another possibility is that a fraction of Si and Fe atoms are in very small grains. Rodríguez (2002) show that the depletion of Fe correlates with the ionization degree, which indicates that dust grains are in small sizes with $a \sim 10$Å.

5. Summary

We observed 14 Galactic star-forming regions with the IRS on board *Spitzer*. [Si II] 35 μm is detected at all the observed positions and [Fe II] 26 μm and [Fe III] 23 μm emissions were detected at more than half of the mapping positions of most targets. The high sensitivity of the IRS enables to detect these emission lines from iron ions widely in low density star-forming regions for the first time. For three group (a) targets, S171, G333.6-0.2, and σ Sco, we provide $(Si^+/N^+)_{as} \sim$ 0.08–0.4 and $(Fe^+/N^+)_{as} \sim$ 0.005–0.01, $<$ 0.05, and 0.03–0.06, respectively, assuming that all the [Si II] 35 μm and [Fe II] 26 μm emission originate from the ionized gas. For both group (a) and (b) targets, we derived $(Si^+/S^{2+})_{as}$ and $(Fe^{2+}/S^{2+})_{as}$ to be 0.03–1 and $<$ 0.08, respectively. We have suggested that those indicate roughly the elemental gas-phase abundance ratio of $(Si/S)_{as}$ and $(Fe/S)_{as}$ in most regions. Together with the estimates in the PDR gas, the results indicate that 3–100% of Si atoms and $<$ 22% of Fe atoms are included in dust grains which are destroyed easily in the ionized or PDR gas in H II regions by the UV radiation, or reside in mantles which are photodesorbed by UV photons, organometallic complexes, or in small grains.

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