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Are SiO molecules the seed of silicate dust around evolved stars?

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Abstract. Silicate is the most popular dust species in the circumstellar envelope of evolved oxygen-rich stars, yet its seed particles have not been well identified. Among the candidates, corundum and SiO attract intense attention and study. SiO was suggested to be the seed particles in early 1980s and has received various supports as well as oppositions. In this work we investigate the relation of SiO maser and silicate dust emission powers. With both our own observation by using the PMO/Delingha 13.7-m telescope and the archival data, a sample is assembled of 21 SiO v=1, J=2-1 sources and 28 SiO v=1, J=1-0 sources that exhibit silicate emission features in the ISO/SWS spectrum. The analysis of their SiO maser and silicate emission power shows a moderate correlation, which agrees with the idea that SiO molecules are the seed nuclei of silicate dust.

Keywords. circumstellar matter, dust, masers, mass loss

1. Introduction

It is generally accepted that silicate dust forms heterogeneously in the circumstellar envelopes of evolved stars. But the nucleation seed particles are not well identified. According to the condensation sequence by temperature, the particles that condense at high temperature are proposed. For example, TiO_2 is the most probable candidate to nucleate first, but it is inefficient in forming the dust at low density due to the low abundance of Ti. Corundum (Al_2O_3) condenses at $\sim$1200 K at low pressures and at $\sim$2000 K at high pressures. Moreover, some spectral features in the infrared are identified to be associated with corundum in the wind of low mass loss rate (10^{-7} $M_\odot$/yr) stars. The problems with corundum are (1) it has no direct molecular progenitors and (2) it is too transparent to be effectively accelerated away from the star by radiation pressure.

SiO is the very abundant oxygen-bearing species and a rather stable condensed phase exists with chemical composition SiO, thus it seems to be the most obvious seed particles of silicate nucleation and was already suggested as the candidate in early 1980s. But the experimental measurements by Nuth & Donn (1982) and subsequent theoretical calculations by Gail & Sedlmayr (1986) found that the effective condensation of SiO takes place only below 600 K under typical M star condition, while the silicate dust is detected at temperature as high as over 1000 K though the dust temperature is below 600 K in the circumstellar envelopes of many evolved stars (Onaka *et al.* 1998). Later, Gai *et al.* (2013) renewed the experiments and re-determined the condensation temperature to be about 700 K. In combination with stellar pulsation that takes the atmosphere to lower temperature, Gail *et al.* (2016) argue that the SiO molecules clustering could trigger the silicate dust formation in Mira variables. On the other hand, Bromley *et al.* (2016) evaluated the nucleation rate of SiO by a bottom-up kinetic modelling and concluded that the kinetics of SiO nucleation is much too slow under the condition of a stellar outflow to explain dust formation above 1000 K. Instead, Gobrecht *et al.* (2018) support corundum as the seed particles. The chemical experiments and calculations agree that the SiO molecules can be the seed particles at low temperatures but not at high temperatures.

The possibility of SiO molecules as the seed particles of silicate dust is investigated by astronomical observation as well. González Delgado *et al.* (2003) derived the SiO gas abundance from their observation of thermal SiO radio emission line. They found that the SiO abundances in all cases are well below the expected from stellar equilibrium chemistry and decrease with mass loss rate, which is interpreted in terms of depletion of SiO molecules by formation of silicate dust grains in the circumstellar envelope.

We tackle this question from the correlation of the SiO maser power and the silicate dust emission intensity. The SiO maser lines are usually detected in the vibrational excited states, different from the thermal line in the vibrational ground state. The SiO maser emission thus locates inside the thermal emission, where dust has hardly formed, and should trace the abundance of the SiO gas that has not been depleted by dust formation. Meanwhile, the silicate dust emission, which is usually optically thin, is an indicator of the mass of silicate dust. A correlation is expected between the SiO maser power and the silicate dust emission intensity if the SiO molecules are the seed of the silicate dust. We further discuss the relation of SiO maser emission and crystalline silicate which is believed to form at higher temperature and closer to the stellar surface than amorphous silicate.

2. Sample, data and method

In order to study the relation of the SiO maser emission power and the silicate emission, the star must be detected in both emissions. We assembled the sample from previous systematic searches for crystalline silicates, namely Gielen *et al.* (2008), Olofsson *et al.* (2009), Jones *et al.* (2012) and Liu *et al.* (2017), meanwhile the ISO/SWS spectrum should be available for the selected candidate. The objects are searched for the SiO maser emission by the PMO/Delingha 13.7-m telescope which resulted in five detections. For the other objects, we looked for the SiO maser observations by Cho *et al.* (2009), Kim *et al.* (2010), and Cho & Kim (2012). Consequently, the final sample consists of 28 (21) sources with the SiO v=1, J=1-0 (J=2-1) emission, which are AGB stars, OH/IR stars, post-AGB stars, planetary nebulae and red supergiant stars (Liu & Jiang 2017).

The SiO maser emission power (Jy km s^{-1}) is calculated by integrating along the velocity. The silicate emission power (W m^{-2}) is decomposed into four components: (1)stellar continuum, (2) dust continuum, (3) amorphous silicate spectral features around 9.7μm and 18μm, and (4) a series of individual narrow features from crystalline silicate (Liu *et al.* 2017), where the sum of (2,3,4) is the total silicate emission intensity and (4) is the crystalline silicate emission intensity.

3. Result and Discussion

In Figure 1 is shown the result of correlation analysis between the SiO maser emission power and the total silicate emission intensity which are normalized to the IRAS/60μm flux to remove the distance effect. With a Pearson correlation coefficient of 0.61 for the SiO J=1-0 line and 0.44 for the SiO J=2-1 line, the silicate emission intensity is moderately correlated with the SiO maser emission. The case of the crystalline silicate has the correlation coefficients of 0.18 and 0.11 respectively, which indicates a null correlation.

Although SiO maser emission is a non-thermal process, the emission power is approximately proportional to the abundance of the SiO molecules at moderate SiO abundances (Bujarrabal (1994)). The silicate emission intensity is proportional to the dust mass in optically thin case as the samples stars mostly are. The correlation implies that the SiO

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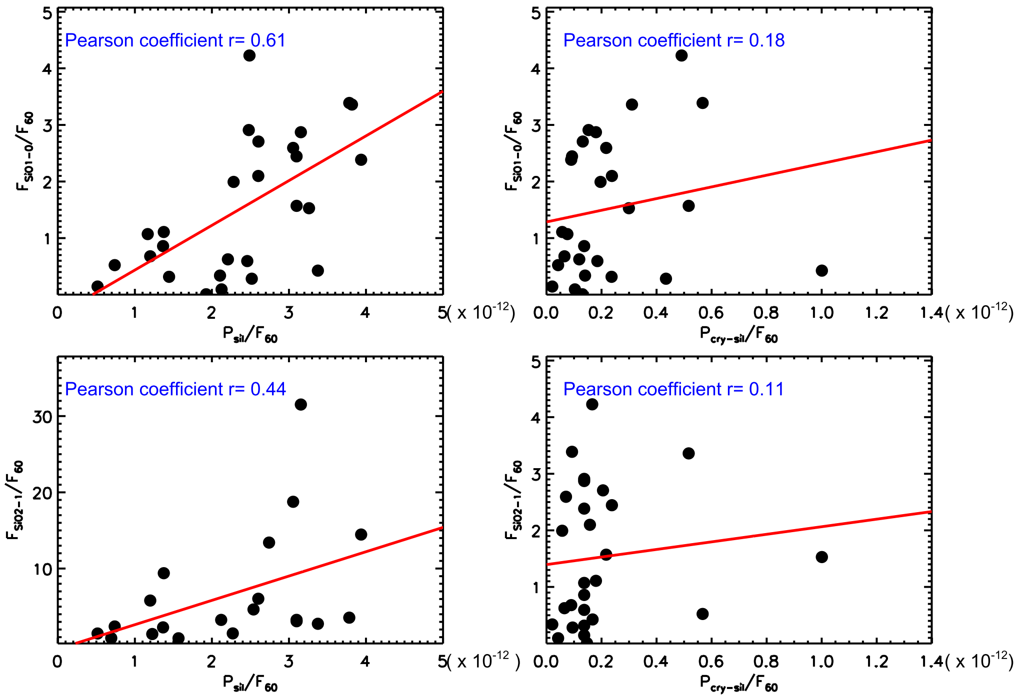

Figure 1. Correlation between the SiO maser line power (J=1-0 (upper) & J=2-1 (lower)) and silicate dust (total (left) and crystalline (right)) emission intensity.

abundance and the silicate dust mass are correlated, which is in line with the idea that the SiO molecules and the silicate dust have a common history in the circumstellar envelope of evolved oxygen-rich stars. The null correlation with crystalline silicate may imply that crystallinity depends more on the temperature than the abundance.

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References

Bromley, S. T., Gómez Martín, J. C., & Plane, J. M. C. 2016, *PCCP*, 18, 26913
Bujarrabal, V. 1994, *A&A*, 285, 953
Cho, S.-H., Chung, H.-S., Kim, H.-G., *et al.* 2009, *ApJS*, 181, 421
Cho, S.-H., & Kim, J. 2012, *AJ*, 144, 129
Gail, H.-P., & Sedlmayr, E. 1986,*A&A*, 166, 225
Gail, H.-P., Wetzel, S., Pucci, A., & Tamanai, A. 2013, *A&A*, 555, A119
Gail, H.-P., Scholz, M., & Pucci, A. 2016, *A&A*, 591, A17
Gielen, C., *et al.* 2008, *A&A*, 490, 725
Gobrecht, D., Decin, L., Cristallo, S., & Bromley, S. T. 2018, *Chem. Phys. Lett.*, 711, 138
González Delgado, D., Olofsson, H., Kerschbaum, F., *et al.* 2003, *A&A*, 411, 123
Jones, O. C., Kemper, F., Sargent, B. A., *et al.* 2012, *MNRAS*, 427, 3209
Kim, J., Cho, S.-H., Oh, C. S., & Byun, D.-Y. 2010,*ApJS*, 188, 209
Liu, J., Jiang, B. W., Li, A., & Gao, J. 2017, *MNRAS*, 466, 1963
Liu, J., & Jiang, B. 2017, *AJ*, 153, 176
Nuth, J. A., & Donn, B. 1982, *J. Chem. Phys.*, 77, 2639
Olofsson, J., Augereau, J.-C., van Dishoeck, E. F., *et al.* 2009, *A&A*, 507, 327
Onaka, T., Yamamura, I., de Jong, T., *et al.* 1998, *Astrophysics and Space Science*, 255, 331

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