A SYSTEMATIC SEARCH FOR THE SPECTRA WITH FEATURES OF CRYSTALLINE SILICATES IN THE SPITZER IRS ENHANCED PRODUCTS

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ABSTRACT

The crystalline silicate features are mainly reflected in infrared bands. The Spitzer Infrared Spectrograph (IRS) collected numerous spectra of various objects and provided a big database to investigate crystalline silicates in a wide range of astronomical environments. We apply the manifold ranking algorithm to perform a systematic search for the spectra with crystalline silicate features in the Spitzer IRS Enhanced Products available. In total, 868 spectra of 790 sources are found to show the features of crystalline silicates. These objects are cross-matched with the SIMBAD database as well as with the Large Sky Area Multi-object Fiber Spectroscopic Telescope (LAMOST)/DR2. The average spectrum of young stellar objects shows a variety of features dominated either by forsterite or enstatite or neither, while the average spectrum of evolved objects consistently present dominant features of forsterite in AGB, OH/IR, post-AGB, and planetary nebulae. They are identified optically as early-type stars, evolved stars, galaxies and so on. In addition, the strength of spectral features in typical silicate complexes is calculated. The results are available through CDS for the astronomical community to further study crystalline silicates.

Key words: catalogs – circumstellar matter – infrared: ISM – infrared: stars – ISM: lines and bands – stars: variables: T Tauri, Herbig Ae/Be

Supporting material: machine-readable tables

1. INTRODUCTION

In the interstellar space, silicates get modified, destroyed, and potentially reformed; they play an important role in the cosmic life cycle of matter. As an important component of circumstellar and interstellar dust, silicates provide information about the size of grains and the chemical composition of dust. Their mid-infrared spectral features can help us to get the information about the density and thermal structure of circumstellar disks and envelopes (see Henning 2010).

All the earlier observations showed that the feature bands of silicates are broad and smooth around 9.7\(\mu\)m and 18\(\mu\)m, respectively (see Molster & Kemper 2005). Dorschner et al. (1995) used laboratory data to identify the carrier of these features to be amorphous olivine silicates. Later, the Infrared Space Observatory (ISO) and the Spitzer Space Telescope obtained a lot of infrared spectra with high sensitivity and high resolution, which opened a new window for us to identify and investigate the spectral features of crystalline silicates. Molster et al. (2002a, 2002b, 2002c) systematically studied the spectral features of crystalline silicates and diversified them into seven distinct complexes using the ISO/SWS (Short Wavelength Spectrometer) and LWS (Long Wavelength Spectrometer) spectra, which are called the 10\(\mu\)m (7–13\(\mu\)m), 18\(\mu\)m (15–20\(\mu\)m), 23\(\mu\)m (22–25.5\(\mu\)m), 28\(\mu\)m (26.5–31.5\(\mu\)m), 33\(\mu\)m (31.5–37.5\(\mu\)m), 40\(\mu\)m (38–44.5\(\mu\)m), and 69\(\mu\)m (50–72\(\mu\)m) complex, respectively.

Crystalline silicates have been identified in various scales (solar system, stars, galaxies, and quasars), such as comet, protoplanetary disk of Herbig Ae/Be stars, and T Tauri stars, debris disks around the main-sequence stars (Li & Greenberg 1998), circumstellar envelopes in post-main-sequence stars (Waters et al. 1996; Sylvester et al. 1999; Molster et al. 2002a; Jiang et al. 2013), very bright infrared galaxies (Spoon et al. 2006; Markwick-Kemper et al. 2007), quasars (Markwick-Kemper et al. 2007; Aller et al. 2012; Xie et al. 2014), etc.

In this work, we present a systematic search for the spectra with features of crystalline silicates from the Spitzer InfraRed Spectrograph (IRS) Enhanced Products (Houck et al. 2004). In Section 2, a brief description is presented about the Spitzer IRS Enhanced Products (Houck et al. 2004). The method we used is manifold ranking (MR) algorithm first proposed by Zhou et al. (2004a, 2004b), which will be described in Section 3.1. The selected objects with crystalline silicate features are cross-identified with the SIMBAD database as well as with the LAMOST optical spectroscopy in Section 3.3.

2. DATA DESCRIPTION

Spectra taken by the IRS (Houck et al. 2004) on the Spitzer space telescope (Werner et al. 2004) are now publicly available. These spectra are produced using the bksub tbl products from SL and LL modules of final SSC pipeline, version 18.18. From the IRS data archive, we found a collection of 16,986 low-resolution spectra. The spectra are merged by four slits: SL2 (5.21–7.56\(\mu\)m), SL1 (7.57–14.28\(\mu\)m), LL2 (14.29–20.66\(\mu\)m), and LL1 (20.67–38.00\(\mu\)m). As crystalline silicates have no features in the SL2 band, we choose the spectra that include all the other three bands: SL1, LL2, and LL1 so that the object has a continuous spectrum from about 7.5–38\(\mu\)m. In this way, five of the seven infrared complexes of crystalline silicates are covered, i.e., the 10, 18, 23, 28, and 33\(\mu\)m complexes. Consequently, 9711 spectra are picked up. Figure 1 shows the signal-to-noise ratio (S/N) distribution of these 9711 spectra.
Figure 1. S/N distribution of the basic 9711 Spitzer/IRS spectra.

Figure 2. Effect of median filtering. The blue spectrum is the observed spectrum, while the red one is the processed spectrum after median filtering.

Figure 3. Example spectrum with crystalline silicates in Jones et al. (2012).
for the three IRS slits, respectively. In order to reduce the noise, median filtering is applied. The main idea of median filtering is to run through the spectrum pixel by pixel, replacing each pixel with the median of neighboring pixels. Here we use median filtering with a width of 5 pixels, which means each pixel is replaced with the median of 5 neighboring pixels. Because the spectral features of silicate dust, even of crystalline silicates, are much wider than the atomic and ionic lines, they are not affected by the median filtering. Figure 2 compares the spectrum before and after the median filtering and proves its efficiency in depressing the high-frequency noise and spikes.

3. SEARCH FOR SPECTRA WITH CRYSTALLINE SILICATES FEATURES

3.1. Method and Result

Considering a sample set \( \mathcal{X} = \{x_1, \cdots, x_q, x_{q+1}, \cdots, x_n\} \), the first \( q \) units are labeled and belong to the same class (here are the known spectra with crystalline silicate features), and the rest are unlabeled (here are 9711 spectra from the Spitzer IRS). Our task is to retrieve the units similar to the labeled ones. In general, the labeled sample is much smaller compared with the whole sample, namely, \( q \ll n \). MR (Zhou et al. 2004a, 2004b) can rank the unlabeled units according to their similarity to the labeled and improve the results by using the relationship between unlabeled and labeled units.

Let \( F: \mathcal{X} \rightarrow R \) denotes a ranking function that assigns to each unit \( x_i \) a ranking value of \( F_i \). Let \( Y = [Y_1, \ldots, Y_n]^{T} \), in which \( Y_i = 1 \) if \( x_i \) is a labeled unit, and \( Y_i = 0 \) otherwise. The procedure of MR is as follows.

![Figure 4](image-url)

**Figure 4.** Upper panel: comparison of \( R@k \) for different settings of \( k \). Lower panel: comparison of \( NI@k \). The legend of the right figure, for example, \( n = 1 \) & 10 represents the comparison between the results of \( n = 1 \) and \( n = 10 \).

| Ranking Range | \( N_{\text{crystalline}} \) | Ranking Range | \( N_{\text{crystalline}} \) |
|---------------|-----------------|---------------|-----------------|
| 1–100         | 98              | 1001–1100     | 41              |
| 101–200       | 91              | 1101–1200     | 30              |
| 201–300       | 80              | 1201–1300     | 22              |
| 301–400       | 78              | 1301–1400     | 13              |
| 401–500       | 76              | 1401–1500     | 7               |
| 501–600       | 74              | 1501–1600     | 4               |
| 601–700       | 70              | 1601–1700     | 2               |
| 701–800       | 74              | 1701–1800     | 1               |
| 801–900       | 60              | 1801–1900     | 0               |
| 901–1000      | 50              | 1901–2000     | 1               |

**Note.** The column of \( N_{\text{crystalline}} \) is the number of spectra with crystalline silicate features.
1. Construct the weighted graph \( G = (X, W) \) by using a kNN (k Nearest Neighbor) graph, where \( W \) is a symmetric adjacency matrix. \( W_{ij} \) represents similarity between unit \( x_i \) and \( x_j \) and is defined by

\[
W_{ij} = \begin{cases} 
\frac{1}{\sigma^2} e^{-d(x_i, x_j)^2/2\sigma^2} & \text{\( x_i, x_j \) are connected and \( i \neq j \)} \\
0 & \text{others,} 
\end{cases}
\]

where \( d(x_i, x_j) \) is the distance between \( x_i \) and \( x_j \), here we use the Euclidean distance, and \( \sigma \) is a constant that controls the strength of the weight.

2. Form the matrix \( S = D^{-1/2}WD^{-1/2} \), where \( D \) is a diagonal matrix with its \((i, i)\)-element equals to the sum of the \( i \)th row of \( W \).

3. Iterate \( F(t + 1) = \alpha SF(t) + (1 - \alpha)Y \) until convergence, where \( \alpha \) is a parameter in \((0, 1)\). The intuitive description of this step is that all the units spread their scores to the nearby units via the weighted graph.

4. Let \( F^* = F(t) \), sort \( F^* \) in descending order and return index rank.

The basis of the labeled sample for MR is the 38 Spitzer/IRS spectra that have crystalline silicate features from Jones et al. (2012), which is a relatively large sample and also taken by Spitzer/IRS. Our mission is to retrieve the spectrum, which has crystalline silicate features similar to the labeled samples. It should be noted that 28 of the 38 Jones’s sources are within the 9711 spectra, which means some duplication. As an example, Figure 3 shows one of the spectra, with prominent emission at the complexes of crystalline silicates. Before the MR algorithm is performed, the median-filtered spectrum is normalized by Minimum–Maximum standardization using the following formula:

\[
sp_i = \frac{sp_i - \min (sp)}{\max (sp) - \min (sp)},
\]

where \( sp_i \) is the \( i \)th pixel of the spectrum \( sp \), so that the maximum is normalized to unique for the convenience of calculation.

In order to verify the completeness and stability of MR, we test the result by varying the number of labeled units. We randomly select a given number \( n \) of spectra with crystalline
silicates features from the 38 sources to compose the labeled sample, while the non-selected spectra with crystalline silicates features and all the 9711 spectra from Spitzer/IRS consist the unlabeled sample. We vary the number $n$ of labeled units in \{1, 10, 19, 28, 37\}. Then we use MR to get the ranking list. We use $n$ to denote the number of labeled units, $R@k$ to denote what fraction of the 38 known spectra with crystalline silicates features are retrieved within the top $k$ ranking spectra and $NI@k$

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**Table 2**

| Feature (μm) | Continuum Interval (μm) |
|--------------|-------------------------|
| 10           | 9.5–11.5                |
| 18           | 17.0–20.0               |
| 23           | 22.3–24.6               |
| 28           | 26.0–31.1               |
| 33           | 31.5–35.0               |

**Table 3**

| Aorkey     | Object          | R.A. (degree) | Decl. (degree) | $W_{eq}(10)$ | $W_{eq}(18)$ | $W_{eq}(23)$ | $W_{eq}(28)$ | $W_{eq}(33)$ |
|------------|----------------|---------------|----------------|--------------|--------------|--------------|--------------|--------------|
| 10665216   | RAW 631        | 12.68487      | −72.62765      | 0.33         | 0.68         | 0.42         | 0.78         | 0.46         |
| 10959616   | HD 268835      | 74.19611      | −69.84022      | 0.08         | 0.15         | 0.10         | 0.13         | 0.11         |
| 12683008   | 2MASS J21380350+5741349 | 324.51465 | 57.69313      | 0.36         | 1.68         | 0.61         | 0.66         | 0.97         |
| 12690688   | HIM C 2-5      | 167.73296     | −76.75901      | 0.06         | 0.26         | 0.20         | 0.37         | 0.31         |
| 12691969   | V* VY Cha      | 167.22729     | −77.03692      | 0.04         | 0.21         | 0.19         | 0.23         | 0.12         |

**Note.** The $W_{eq}(10)$, $W_{eq}(18)$, $W_{eq}(23)$, $W_{eq}(28)$ and $W_{eq}(33)$ are the equivalent widths of the 10, 18, 23, 28 and 33 μm features, respectively. (This table is available in its entirety in machine-readable form.)
to denote \( m/k \) where \( m \) is the number of intersection within the top \( k \) ranking spectra between different \( n \).

The test results of different \( n \) are displayed in Figure 4. From the left figure, it can be seen that the non-selected spectra with crystalline silicate features are found within the top 900 ranking when \( n = 10 \), 19, 28, and 37, while 97\% non-selected spectra are found within the top 1300 ranking when \( n = 1 \). Meanwhile, the right figure tells that the ranking list is stable against the change of the number of labeled samples when \( n \geq 19 \).

The top 2000 ranking samples are selected for a final review. 868 spectra are found to show crystalline silicate features (see Table 1). From Table 1, we can see the spectrum has higher probability with crystalline silicate features when its ranking is higher, and we can hardly find any spectra with crystalline silicate features when their rankings are above 2000. The spectra of the sources ranking at 2, 4, 8, 16, 32, 64, 128, 256, and 512 are displayed in Figure 5. The S/N distribution of these 868 spectra in Figure 6 indicates that most of the sources have \( S/N > 10 \) in the SL1 and LL2 bands (\( \sim 7-21 \mu m \)), much better than the average of primordial 9711 sample objects.

### 3.2. Intensity of the Spectral Features of Crystalline Silicates

We consider that the observed flux is contributed by dust continuum \( (F_{\text{cont}}) \), and dust spectral features from both amorphous silicates \( (F_{\text{amo}}) \) and crystalline silicates \( (F_{\text{crys}}) \):

\[
F_{\text{obs}} = F_{\text{cont}} + F_{\text{amo}} + F_{\text{crys}}.
\]  

(3)

For each spectrum, we first modeled the dust continuum by fitting a piecewise polynomial of degree 3 to anchor points. Following the analysis of Watson et al. (2009), we selected the following anchor points: 7.57–7.94, 13.02–13.50, 30.16–32.19, and 35.07–35.92 \( \mu m \), which are not affected by solid-state emission features. After the continuum is subtracted, the amorphous silicate features around 10 and 18 \( \mu m \) are fitted by

\[
F_{\text{amo}}(\nu) = B(T_{\text{amo}}, \nu) \times Q_{\text{amo}}(\nu),
\]  

(4)

where \( B(T_{\text{amo}}, \nu) \) is a blackbody radiation at the temperature \( T_{\text{amo}} \) and \( Q_{\text{amo}}(\nu) \) is the absorption efficiency of amorphous silicate. The absorption efficiency of the amorphous silicate is based on the optical constants of Ossenkopf et al. (1992) assuming the dust to be spherical with radii \( a = 0.1 \mu m \), following the numerals of Jiang et al. (2013). The temperature of the amorphous silicate is adjusted in the range of 40–1200 K at an interval of 10 K to achieve the best fitting. The residual after subtracting the dust continuum and the spectral features of the amorphous silicate is taken to be the spectral features of the crystalline silicate. Figure 7 shows an example. It can be seen that the amorphous silicate features take a priority over the crystalline silicate since fitting the amorphous spectral features is maximized to match the spectrum after the continuum is subtracted. This fitting may underestimate the intensity of the spectral features of crystalline silicate, which means we are obtaining a lower limit of the intensity ratio of crystalline to amorphous silicate features in the following.

The intensity of crystalline silicate bands is measured in order to understand their properties in relation to stellar parameters. Here the equivalent widths of the 10, 18, 23, 28, and 33 \( \mu m \) features, \( W_{\text{eq}} \) is defined as

\[
W_{\text{eq}} = \sum_{\lambda} \frac{F_{\text{crys}}}{\sigma_{\text{crys}}} \Delta \lambda.
\]  

(5)

The wavelength interval of each feature agrees with that defined by Molster et al. (2002a) and described in Section 1 (see Table 2). The results of the equivalent widths in each band are listed in Table 3.

The significance level of the crystalline silicate is calculated in each band as

\[
S/U = \frac{F_{\text{crys}}}{\sigma_{\text{crys}}},
\]  

(6)

where \( F_{\text{crys}} \) is crystalline silicate flux and \( \sigma_{\text{crys}} \) is the uncertainty in the measured flux,

\[
F_{\text{crys}} = \sum_{\lambda} (F_{\text{obs}} - F_{\text{cont}} - F_{\text{amo}}) \Delta \lambda
\]  

(7)

\[
\sigma_{\text{crys}}^2 = \sum_{\lambda} ((X_{\text{obs}} * (F_{\text{cont}} + F_{\text{amo}}))^2 + \sigma^2) \Delta \lambda^2,
\]  

(8)
## Table 4
Results of Significance Level and Crystallinity

| Aorkey     | Object          | R.A. (degree) | decl. (degree) | $S/U(10)$ | $S/U(18)$ | $S/U(23)$ | $S/U(28)$ | $S/U(33)$ | Crystallinity (%) | Crystallinity_min (%) |
|------------|-----------------|---------------|----------------|-----------|-----------|-----------|-----------|-----------|-------------------|-----------------------|
| 10665216   | RAW 631         | 12.68487      | -72.62765      | 0.53      | 0.45      | 0.65      | 0.85      | 0.56      | 38.5              | 13.1                  |
| 10959616   | HD 268835       | 74.19611      | -69.84022      | 0.19      | 0.14      | 0.18      | 0.15      | 0.14      | 28.0              | 4.5                   |
| 12683008   | 2MASS J21380350+5741349 | 324.51465 | 57.69313       | 0.49      | 0.92      | 0.96      | 0.58      | 0.44      | 66.5              | 20.5                  |
| 12690688   | HIM C 2-5       | 167.73296     | -76.75901      | 0.14      | 0.25      | 0.39      | 0.41      | 0.40      | 52.3              | 9.7                   |
| 12691969   | V* VY Cha       | 167.22729     | -77.03692      | 0.09      | 0.17      | 0.35      | 0.25      | 0.16      | 34.0              | 6.6                   |

**Note.** The $S/U(10)$, $S/U(18)$, $S/U(23)$, $S/U(28)$, and $S/U(33)$ are the significance levels of the 10, 18, 23, 28, and 33 $\mu$m features of crystalline silicate, respectively. (This table is available in its entirety in machine-readable form.)
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Table 5
Results of SIMBAD Type

| Object            | R.A. (degree) | decl. (degree) | SIMBAD Type          | SIMBAD Spectral Type |
|-------------------|---------------|----------------|----------------------|----------------------|
| RAW 631           | 12.6847       | −72.62765      | Carbon Star          | C                    |
| HD 268835         | 74.1961       | −69.84022      | Blue supergiant star | B[e]                 |
| 2MASS J21380350+5741349 | 324.5146      | 57.69313       | T Tau-type Star      | G9                   |
| HJM C 2-5         | 167.73296     | −76.75901      | Pre-main-sequence Star | M6e                  |
| V7 VY Cha         | 167.22729     | −77.03692      | Variable Star of Orion Type | M0.5               |

(The table is available in its entirety in machine-readable form.)

Table 6
Summary of SIMBAD Type

| SIMBAD Type                              | Number | SIMBAD Type                              | Number | SIMBAD Type                              | Number |
|------------------------------------------|--------|------------------------------------------|--------|------------------------------------------|--------|
| Young Stellar Object                     | 132    | Planetary Nebula                         | 8      | Galaxy                                   | 1      |
| Variable Star of Orion Type             | 128    | Brown Dwarf                              | 7      | Reflection Nebula                        | 1      |
| T Tau-type Star                          | 100    | Variable Star of RV Tau-type             | 6      | Possible Planetary Nebula                | 1      |
| Herbig Ae/Be star                        | 55     | Blue supergiant star                     | 5      | Variable of BY Dra type                  | 1      |
| Pre-main-sequence Star                  | 54     | Flare Star                               | 5      | Dark Cloud (nebula)                      | 1      |
| Emission-line Star                      | 36     | Double or multiple star                  | 4      | Star in Association                      | 1      |
| Star                                     | 28     | Nova                                     | 3      | Variable Star of irregular type          | 1      |
| Variable Star of Mira Cet type          | 25     | S Star                                   | 3      | Wolf–Rayet Star                          | 1      |
| Post-AGB Star (proto-PN)                | 20     | Seyfert 1 Galaxy                         | 3      | Possible Red supergiant star             | 1      |
| Red supergiant star                     | 19     | Low-mass star ($M < 1$solMass)           | 2      | Star suspected of Variability            | 1      |
| Young Star                              | 18     | Emission Object                          | 2      | Variable Star of RR Lyr type             | 1      |
| Infrared source                         | 15     | Variable Star of FU Ori type             | 2      | Extra-solar Confirmed Planet             | 1      |
| Young Stellar Object Candidate          | 14     | X-ray source                             | 2      | Variable Star of delta Sct type          | 1      |
| T Tau star Candidate                    | 12     | Dense core                               | 2      | Variable Star with rapid variations      | 1      |
| Star in Cluster                         | 12     | Evolved supergiant star                  | 2      | SuperNova Remnant                        | 1      |
| Asymptotic Giant Branch Star (He-burning) | 12  | Be Star                                  | 2      | Pulsating variable Star                  | 1      |
| OH/IR star                              | 11     | Carbon Star                              | 1      | Brown Dwarf Candidate                    | 1      |
| Long-period variable star               | 11     | Object of unknown nature                 | 1      | ...                                       | ...    |
| Semi-regular pulsating Star             | 9      | Post-AGB Star Candidate                  | 1      | ...                                       | ...    |

Note. The number is the amount of corresponding SIMBAD types.

where $\sigma$ is statistical uncertainty in each resolved element of the spectra, and $X_{\text{fac}}$ is the uncertainty in the determination of the underlying continuum and amorphous silicate, which we conservatively assumed to be 10% ($X_{\text{fac}} = 0.1$). The value of $X_{\text{fac}}$ is the same as that adopted by Mittal et al. (2015) since we both deal with the Spitzer/IRS spectrum and determine the continuum in a similar way. In addition, some experiments are carried out by choosing the neighbouring points of default anchor points for the determination of continuum and amorphous silicate’s features. It is found that the scattering of the dust continuum and amorphous silicate features are both less than 0.1. The results of the significance level in each band are listed in Table 4.

We also calculate the crystallinity, which can provide a quantitative measure of the percentage of crystalline silicate and can be defined as

$$\text{Crystallinity} = \frac{\sum \lambda f_{\text{cryst}} \Delta \lambda}{\sum \lambda f_{\text{cryst}} \Delta \lambda + \sum \lambda f_{\text{amo}} \Delta \lambda}.$$  \hspace{1cm} (9)

The results of crystallinity are listed in Table 4. Considering that amorphous silicates can contribute to the continuum emission, a lower limit of crystallinity defined by flux ratio is also calculated as

$$\text{Crystallinity}_\text{min} = \frac{\sum \lambda f_{\text{cryst}} \Delta \lambda}{\sum \lambda f_{\text{obs}} \Delta \lambda}. \hspace{1cm} (10)$$

The results are in Table 4.

3.3. Identification in the SIMBAD and LAMOST/DR2 Databases

The 868 spectra are cross-identified with the SIMBAD database to learn the types of sources, and the results are presented in Table 5. Removing duplicate sources, there are 790 sources whose classifications are summarized in Table 6. Many of the sources are in the early stage of evolution, including the Orion-type variables, T Tauri stars, pre-main-sequence stars, Herbig Ae/Be stars, and FU Ori type. The second most popular class is in the late stage of evolution. They are mostly the low-mass evolved stars such as AGB stars, OH/IR stars, post-AGB stars or protoplanetary nebulae, and planetary nebulae, as well as carbon stars and S-type stars. At the same time, the massive stars in the late stage of evolution are also present, such as red and blue supergiants. The detection of crystalline silicates has been widely reported in the early and late stages of stellar evolution. In addition, crystalline silicate emission is found in different types of
variables, such as nova, BY Dra type, RR Lyr type, delta Sct type, and several types of long-period pulsating variables. Many types have only one object in our identified sample of crystalline silicate emitters. Confirmation of these types of objects requires more serious investigation.

The average spectrum is calculated for the types that have more than five objects by a weighted mean according to the flux intensity. It should be noted that the objects can generally be divided into two major classes, i.e., the young stellar objects and the evolved stars, even though the SIMBAD types are various. The young stellar objects may include all of the types in the early stage of evolution, such as pre-main-sequence stars and proto-stars, while pre-main-sequence stars may include the low-mass T Tau-type star (which can also be an Orion-type variable) and the massive Herbig Ae/Be star. On the other hand, AGB stars, OH/IR stars, post-AGB stars, planetary nebulae, etc. are all in the late evolutionary stage of low-mass stars. The variable stars (semi-regular, long-period, Mira-type) are overlapped with the evolved stars. As shown in Figure 8, we divided the objects into four major classes: young stellar objects, evolved stars, variable stars and other types. In the final, the average spectra of all young stellar objects and all evolved stars are compared in Figure 8(e). It can be seen that the young stellar objects generally have colder continua than...
Table 7
Results of Cross-identification with LAMOST

| Aorkey | Object | R.A. (degree) | decl. (degree) | Class | Subclass | z    | Hα   | SIMBAD Type          | SIMBAD Spectra Type |
|--------|--------|---------------|----------------|-------|----------|------|------|----------------------|---------------------|
| 14971648 | 2MASS J03022104+1710342 | 45.58757 | 17.17621 | STAR | M3       | −2.59E-04 | 1 | T Tauri-type Star    | M3    |
| 5633280  | NAME LDN 1455 IRS 2 | 51.94873 | 30.20122 | STAR | K5       | −7.74E-04 | 1 | Dense core             | …     |
| 22031616 | EM* LkHA 352A | 52.2125 | 31.3051 | STAR | M5       | 3.32E-05  | 1 | Emission-line Star    | M4.5   |
| 22032384 | 2MASS J03279019+3119548 | 52.21324 | 31.33186 | STAR | M0       | 5.19E-05  | 1 | Young Stellar Object | K7.0   |
| 22032128 | 2MASS J03285663+3118356 | 52.23595 | 31.30986 | STAR | M2       | 2.12E-03  | 1 | Young Stellar Object | M1.5   |

Note. z is the redshift of object. In the column of Hα, 1, 0, and −1 mean the object has a strong Hα emission line, no strong Hα line and a strong Hα absorption line, respectively. (This table is available in its entirety in machine-readable form.)
evolved stars. In respect to the spectral features of crystalline silicates, the evolved stars have wider features around 10 μm, and show a more evident peak at about 11.2 μm. In comparison with the absorption coefficient of typical crystalline silicates—forsterite and enstatite—such a profile points to a richer amount of forsterite in the evolved stars than in young stellar objects. Consistently, the features at 20 and 24 μm of forsterite are also prominent. Nevertheless, it should be noted that the young stellar objects exhibit diversity among sub-types: T Tau-type stars have a raised red wing, like evolved stars, Herbig Ae/Be stars have a raised blue wing, and the Orion-type variables show a flat top around 10 μm. Such a distinction between T Tau-type stars and Herbig Ae/Be stars is different from previous studies. It was believed that the spectra of T Tau-type stars in the 10 μm range trace the warm inner disk and thus show more enstatite features (e.g., Bouwman et al. 2008) while Herbig Ae/Be stars trace the cold outer disk and thus more forsterite features (e.g., Juhász et al. 2010). Our average spectra show a contrary tendency. A possible reason for this discrepancy is that the average spectrum may be affected by the dust continuum. Removing the dust continuum emission, we can see that the T Tau-type stars show the features dominated by enstatite and the Herbig Ae/Be stars show the features dominated by forsterite in the 10 μm range, as can be seen in Figure 8(f). This is then consistent with the previous conclusion. On the other hand, the evolved stars conform to the average spectrum. AGB stars, OH/IR stars, post-AGB stars, and planetary nebulae all point to a raised red wing of the 10 μm feature, indicating the dominant role of forsterite. This consistent scenario implies similar conditions for crystallization of silicate dust in the circumstellar envelope of evolved stars. One exception is the RV Tau-type variables, which show no dominance of spectral features of forsterite. As RV Tau-type stars are usually post-AGB stars in a binary system, there may be a disk-like structure that influences the composition of crystalline silicates.

The identified sample is also cross-matched with the LAMOST/DR2 catalog resulting in 91 identifications. As LAMOST is an optical spectroscopic survey, the objects are classified spectroscopically, with their types listed in Table 7 and the summary of spectral types in Table 8. Very interestingly, 83 of 91 (i.e., 91%) sources have strong Hα emission lines. The Hα emission is usually associated with the circumstellar disk or envelope in early-type stars or chromospheric activity in late-type dwarf stars. Whether the condition to excite the Hα emission is related to the crystallization of silicates deserves further investigation. From this high percentage of Hα emission occurrence in the LAMOST identified sample, there should be some connection between these two phenomena. The types span the stellar classes M-, K-, G-, F-, and A-types, and one white dwarf and one quasar. A careful check confirmed the spectral classification, except the white dwarf identification. On the other hand, three stars have strong Hα absorption line. Figure 9 shows one optical LAMOST spectrum with the Hα emission line.

4. SUMMARY

We performed a systematic search for objects with spectral features of crystalline silicate in the Spitzer/IRS enhanced products using the MR method. The primary results of our study are as follows.

1. We identified 790 sources whose IRS spectra present the crystalline silicates’ features.
2. The equivalent widths of the 10, 18, 23, 28, and 33 μm features of each spectrum are calculated to characterize the strengths of crystalline silicates features.

![Figure 9. One LAMOST optical spectra with Hα emission line. The Hα line is shown in detail in the inset.](image-url)
3. The sources with crystalline silicates are cross-identified in the SIMBAD database for the type of each object. The average spectrum is calculated for the types with more than five objects. It is found that the average spectrum of young stellar objects shows a variety with the features dominated either by enstatite or by forsterite, while the evolved stars all show dominance of the spectral features of forsterite in AGB, OH/IR stars, post-AGB stars, and planetary nebulae.

4. The crystalline silicate stars are cross-identified with the LAMOST spectroscopy, which results in 91 optically identified objects. It is found that 83 (91%) of them show Hα emission line.

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