A New Infrared Photometric Study of Intrinsic and Extrinsic S-type Stars

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Abstract

We collect all known intrinsic and extrinsic S-type stars to discuss their infrared properties and find their difference in the infrared using photometric data from the Two Micron All Sky Survey, Wide Field Infrared Survey Explorer, and Infrared Astronomical Satellite missions. Then we look for the diagnosis to extract intrinsic S-type stars from the large unclassified sample. We found that, statistically, intrinsic S-type stars have larger infrared excesses than extrinsic S-type stars in the wavelength region of 1–60 μm due to thicker dusty circumstellar envelopes. We also found that only intrinsic S-type stars occupy the reddest color areas in all of the two-color diagrams we presented. Finally, 172 new intrinsic S-type stars are presented in this paper. This makes the number of known intrinsic S-type stars almost double. In addition, some intrinsic and extrinsic S-type stars have power-law distributions in some two-color diagrams with the wavelength longer than 5 μm. The possible reason for this is also discussed.

Key words: circumstellar matter – infrared: stars

Supporting material: machine-readable tables

1. Introduction

S-type stars have been traditionally considered for a long time as intermediate red giants between M-type stars and carbon stars as in the evolution sequence M–S–C at the asymptotic giant branch (AGB) phase. The spectra of S-type stars are characterized by the absorption bands of ZrO and LaO molecules in the photosphere. However, About 30 yr ago this idea has been changed that some nonvariable S-type stars without the element of Technetium (Tc) may be in the binary system (Jorissen & Mayor 1988, 1992) at the red giant branch (RGB) or the thermally pulsing asymptotic giant branch (TP-AGB) phases (Busso et al. 1992). In fact, Iben & Renzini (1983) hinted the existence of such S-type stars. Now we know that there are actually two categories of S-type stars. They are as follows.

1. Intrinsic S-type stars that follow the M–S–C evolution sequence and show Tc lines in their optical spectra. They are also called Tc-rich S-type stars or S-type stars with Tc.

2. Extrinsic S-type stars are in a binary system with a white dwarf (WD) and have enhanced s-process elements at the stellar surface as the result of mass transfer from a former AGB star (now the WD) to a less evolved companion (now the S-type star), but without Tc lines in their optical spectra. They are also called Tc-deficient S-type stars or S-type stars without Tc.

In the intrinsic S-type star the third dredge-up process (the signature of s-process elements) is presently at work while in the extrinsic S-type star s-process elements are transferred to a less evolved companion in a binary system. Among elements present in the atmospheres of intrinsic S-type stars there is the element Tc with a half lifetime of about 2 × 10^7 yr, while in the extrinsic S-type star this element has already decayed. Therefore the presence of Tc is well discriminating the intrinsic S-type star from the extrinsic S-type star (Iben & Renzini 1983; Kipper 1991; Johnson et al. 1993).

Several methods can be used to distinguish between extrinsic S-type stars and intrinsic S-type stars; a direct way is to detect Tc lines (Jorissen 2004). However, this is generally difficult since these lines are very weak and lie in a spectral region crowded with many other lines. Fortunately, some indirect methods have been suggested such as: (1) for extrinsic S-type stars the WD companion in a binary system can be directly detected in the UV region if it is warm enough. This has been done by Johnson et al. (1990, 1993). However, up to now only a small amount of S-type stars have UV observations from the International Ultraviolet Explorer. (2) Variations of the periodic radial velocity can be observed for extrinsic S-type stars in a binary system (Jorissen & Mayor 1988, 1992). However, it is limited by their long orbital periods. (3) The high-excitation emission line of He I (10830 Å) has been detected in the spectra of extrinsic S-type stars, while in the spectra of intrinsic S-type stars this line is lacking (Brown et al. 1990). However, this line almost reaches the cutoff wavelength of the response curve in the current CCD. (4) The different infrared colors of the two categories of S-type stars can serve as another important criterion (Chen & Kwok 1993; Groenewegen 1993; Jorissen et al. 1993). Johnson (1992) well summarized these methods to distinguish between intrinsic S-type stars and extrinsic S-type stars.

The unstable element Tc was first identified for some M, S, and carbon stars by Merrill (1952). Little-Marenin & Little (1979) first made the spectral observation of 90 late-type stars (including 10 S-type and MS-type stars) and concluded that the stars with Tc are in Population I, while the stars without Tc are in Population II. Iben & Renzini (1983) discussed the status of the element Tc in the AGB phase and hinted at the existence of extrinsic S-type stars in the binary system. Then Little et al. (1987) made the spectral observation for about 280 late-type stars (including 24 S-type and MS-type stars) to identify some intrinsic S-type stars and extrinsic S-type stars. They pointed
out that single S-type stars all have Tc and that extrinsic S-type stars should be in the binary system. Smith & Lambert (1988) gave high-resolution spectra for 40 MS-type and S-type stars to search for the presence of Tc. They suggested that intrinsic S-type stars are currently thermally pulsing AGB stars undergoing third dredge-up while extrinsic S-type stars represent the coolest members of the barium star class. Brown et al. (1990) made observations of the radial velocity and the He I (10830 Å) triplet for some MS-type and S-type stars. They suggested that the He I features and radial-velocity variations in extrinsic MS-type and S-type stars are both caused by the presence of WD companions. Groenewegen (1993) studied the discrimination between intrinsic S-type stars and extrinsic S-type stars using their infrared properties from the visual and Infrared Astronomical Satellite (IRAS) observations. Groenewegen found that intrinsic S-type stars have larger infrared excesses from circumstellar envelopes while extrinsic S-type stars are consistent with stellar blackbodies with no or very little infrared excesses. Groenewegen also suggested that extrinsic S-type stars might be 50%–75% of S-type stars in an optically complete sample. Jorissen et al. (1993) investigated the infrared properties for some S-type stars using the Caltech Infrared Catalog (IRC) and the IRAS data. They pointed out that the frequency of intrinsic S-type stars may be less than 50%. Chen & Kwok (1993) studied the circumstellar properties for about 150 S-type stars using the IRAS low-resolution spectra (LRS). They found that the silicate emission feature only appeared for intrinsic S-type stars. Chen et al. (1998) found that an S-type star whose energy distribution can be fitted by a double blackbody curve is likely to be an intrinsic S-type star, whereas candidates of extrinsic S-type stars can be found from sources whose energy distribution can be fitted by a single blackbody curve. Wang & Chen (2002) made the JHK observations for a number of S-type stars. Together with the IRAS photometric and the LRS data they found that about 100 stars are very like extrinsic S-type stars. Lebzelter & Hron (2003) confirmed that only a small fraction of the semiregular variables show Tc lines. However, they also found a significant number of Miras without Tc. Yang et al. (2006) searched the new candidates of intrinsic and extrinsic S-type stars using the Two Micron All Sky Survey (2MASS), IRAS, and Midcourse Space Experiment (MSX) data. Finally they found about 150 candidates of extrinsic S-type stars and 250 candidates of intrinsic S-type stars. Recently infrared properties of about 600 S-type and related stars have been investigated by Guandalini & Busso (2008) using 2MASS, IRAS, Infrared Space Observatory (ISO), and MSX data. They identified about 40 extrinsic S-type stars and about 120 intrinsic S-type stars.

In this paper we attempt to collect all known intrinsic S-type stars and extrinsic S-type stars, and investigate the difference of their infrared properties using 2MASS, Wide Field Infrared Survey Explorer (WISE), and IRAS data. Then the diagnosis to distinguish both kinds of S-type stars is discussed.

It is noted that the WISE data are used first time for the study of these S-type stars in this paper. The WISE mission has completed an all-sky survey in the mid-infrared (Wright et al. 2010). WISE performed observations in four bands, W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm), and WISE all-sky data were released in 2012 March 14. This survey extended the 2MASS All Sky Survey into the mid-infrared and connected it with far-infrared observations by IRAS.

2. Sample Selection and Data Processing

We have collected almost all of the known intrinsic S-type stars and extrinsic S-type stars from the literature (the candidates are not included) to study their infrared color properties using 2MASS, WISE, and IRAS data. Finally 151 certain extrinsic S-type stars and 190 certain intrinsic S-type stars are found. The infrared data for extrinsic S-type stars and intrinsic S-type stars are listed in Tables 1 and 2, respectively. In Tables 1 and 2 the contents are: (1) the star number in this paper; (2) the number in the General Catalog of Galactic S-Stars (GCGSS, simply CSS in this paper) from Stepheson (1984) and Stephenson (1990), simply CSS2; (3) the star name; (4) the star position in the epoch of 2000; (5) the 2MASS JHK magnitudes, where if the empty is showing in the observational error position, it means the upper limit value, which is not used for the data analysis below; (6) the WISE magnitudes in four bands, where if the empty is showing in the observational error position, it means the upper limit value, which is not used for the data analysis below; (7) the Galactic extinction coefficient AV derived in this paper; and (8) the identified IRAS Point Source Catalog/Faint Source Catalog counterpart. In addition, in the note of Table 1 the reference of the source origin is indicated for both Tables 1 and 2. Note that in the context only small parts of Tables 1 and 2 are shown. The full versions of Tables 1 and 2 can be found in the supplemental material as the online data.

The cross-identifications between S-type stars and 2MASS/WISE counterparts are made from Cutri et al. (2012) using the radius of 2″. The cross-identifications of IRAS counterparts are made according to the positional error ellipse of the source, because it has a 95% confidence level (Beichman et al. 1988). We try to extract observational data from the AKARI and Herschel missions, but only very few counterparts are found. Therefore, for statistical purposes those data are not used in this paper.

For the data from 2MASS and WISE, the Galactic extinction correction is needed. We use the Galactic extinction law of Schlegel et al. (1998) for 2MASS data and Yuan et al. (2013) for WISE data, respectively. The Galactic extinction is corrected according to the relation from van Herk (1965),

\[ A_V = 0.14 \csc b \left[ 1 - \exp(-10^{-2}d \sin |b|) \right], \]

where b is the Galactic latitude and d is the distance in parsecs. We also know another relation,

\[ M_K = K + 5 - 5 \log d - A_K, \]

where \( M_K \) and \( A_K \) are the absolute magnitude and the Galactic interstellar extinction coefficient in the K band, respectively. In addition, from Schlegel et al. (1998) we know

\[ A_K = 0.11 A_V. \]

Furthermore, Feast et al. (1982) pointed out that \( M_K = -8.0 \) can be adopted for carbon stars, S-type stars, and related stars, thus iterations for \( d \) and \( A_K (A_V) \) are made to derive the final \( A_K (A_V) \).

Note that the 2MASS and WISE data used below are all corrected for the Galactic extinction according to the method here.
Table 1
Infrared Observation of Known Extrinsic S-type Stars

| No. | CSS | Name       | R.A.(2000) | Decl.(2000) | J    | Jε   | H    | Hε   | K    | Kε   | W1   | W1ε  | W2   | W2ε  | W3   | W3ε  | W4   | W4ε  | Av   | IRAS | References |
|-----|-----|------------|------------|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----|--------|------------|
| 001 | 3   | HD 310     | 000736.59  | -621854.3   | 4.212| 0.270| 3.246| 0.198| 3.023| 0.282| 3.188| 0.109| 2.566| 0.045| 2.997| 0.011| 2.888| 0.016| 0.09 | 0051-6235 | 2       |
| 002 | 10  | IRAS 00300 | 003256.00  | +635908.2   | 6.372| 0.021| 5.201| 0.047| 4.774| 0.017| 4.531| 0.088| 4.329| 0.048| 4.532| 0.015| 4.328| 0.023| 3.09 | 00300+6342 | 13      |
| 003 | 16  | OS Cas     | 005038.46  | +601307.3   | 5.815| 0.026| 4.799| 0.024| 4.244| 0.036| 4.029| 0.109| 3.785| 0.055| 3.874| 0.015| 3.399| 0.022| 2.00 | 00476+5956 | 13      |
| 004 | 22  | CR Psc     | 010512.34  | +191150.0   | 3.671| 0.260| 2.757| 0.212| 2.482| 0.514| 2.884| 0.130| 2.329| 0.090| 2.032| 0.006| 2.089| 0.012| 0.18 | F01025+1855 | 1       |
| 005 | 26  | DT Psc     | 011404.91  | +283146.5   | 2.734| 0.298| 1.858| 0.218| 1.637| 0.260| 2.901| 0.038| 1.854| 0.013| 1.350| 0.004| 1.348| 0.018| 0.18 | 01113+2815 | 5       |
| 006 | 39  | HD 9810    | 013114.28  | -785738.9   | 5.171| 0.037| 4.287| 0.204| 4.054| 0.240| 3.935| 0.119| 3.671| 0.054| 3.941| 0.015| 3.812| 0.021| 0.18 | 01309-7913 | 2       |
| 007 | 45  | BD+21 255  | 015419.70  | +215320.6   | 5.286| 0.027| 4.483| 0.192| 4.290| 0.308| 4.110| 0.106| 3.739| 0.055| 4.019| 0.015| 3.917| 0.020| 0.18 | 01515+2138 | 8       |
| 008 | 47  | IRAS 02048 | 020831.00  | +622244.5   | 6.664| 0.027| 5.581| 0.034| 5.217| 0.020| 5.012| 0.070| 5.002| 0.032| 4.993| 0.015| 4.842| 0.029| 3.81 | 02048+6208 | 13      |
| 009 | 64  | IRAS 02424 | 024623.20  | +600820.2   | 7.802| 0.024| 6.607| 0.020| 6.161| 0.029| 5.893| 0.052| 6.045| 0.023| 5.757| 0.015| 5.285| 0.035| 5.72 | 02424+5955 | 13      |
| 010 | 78  | TYC 3325-367-1 | 033950.79 | +510630.5 | 4.931| 0.037| 3.888| 0.236| 3.318| 0.296| 3.303| 0.145| 2.892| 0.057| 3.240| 0.011| 3.082| 0.017| 1.45 | 03361+5056 | 10      |

References. (1) Groenewegen (1993); (2) Van Eck et al. (2000); (3) Little-Marenin & Little (1979); (4) Little et al. (1987); (5) Smith & Lambert (1988); (6) Brown et al. (1990); (7) Johnson (1992); (8) Jorissen et al. (1993); (9) Jorissen et al. (1998); (10) Wang & Chen (2002); (11) Uttenthaler et al. (2007); (12) Vanture et al. (2007); and (13) Guandalini & Busso (2008).

(This table is available in its entirety in machine-readable form.)
Table 2
Infrared Observation of Known Intrinsic S-type Stars

| No. | CSS | Name       | R.A. (2000) | Decl. (2000) | J   | J_e  | H   | H_e  | K   | K_e  | W1  | W1_e | W2  | W2_e | W3  | W3_e | W4  | W4_e | Av  | IRAS | Note  |
|-----|-----|------------|-------------|--------------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|-----|------|
| 001 | 1346| W Cet     | 000207.53   | -144033.0    | 3.332| 0.244| 2.397| 0.218| 2.047| 0.266| 2.567| 0.053| 1.699| 0.195| 1.503| 0.014| 0.935| 0.010| 0.09 | 23595-1457 | 4    |
| 002 | 8   | T Cet     | 002146.27   | -200326.3    | 0.496| 0.194| -0.482| 0.224| -0.808| 0.276| 2.100| 0.322| 0.685| 0.264| -1.677| 0.240| -2.252| 0.001| 0.09 | 00192-2020 | 1    |
| 003 | 9   | R And     | 002401.74   | +383436.9    | 2.024| 0.278| 0.765| 0.170| 0.122| 0.226| 1.767| ...  | 1.160| 0.008| -1.985| 0.254| -2.843| 0.001| 0.27 | 00213+3817 | 3    |
| 004 | 12  | U Cas     | 004621.12   | +481438.7    | 4.329| 0.258| 3.392| 0.238| 2.878| 0.306| 2.689| 0.165| 1.889| 0.020| 1.804| 0.010| 1.550| 0.010| 0.45 | 00435+4758 | 3    |
| 005 | 13  | V661 Cas  | 004654.58   | +635605.9    | 5.581| 0.018| 4.289| 0.021| 3.622| 0.292| 3.310| 0.181| 2.980| 0.100| 3.050| 0.016| 2.660| 0.019| 2.09 | 00439+6339 | 13   |
| 006 | 20  | V365 Cas  | 010053.15   | +563645.1    | 2.379| 0.190| 1.408| 0.150| 1.013| 0.216| 2.433| 0.118| 1.816| 0.027| 0.753| 0.008| 0.302| 0.007| 0.54 | 00578+5620 | 13   |
| 007 | 29  | V899 Cas  | 012204.40   | +665014.0    | 4.823| 0.228| 3.400| 0.194| 2.716| 0.274| 2.608| 0.234| 2.159| 0.082| 2.130| 0.010| 1.744| 0.015| 1.09 | 01186+6634 | 13   |
| 008 | 40  | V911 Cas  | 013946.83   | +594229.4    | 5.732| 0.026| 4.798| 0.038| 4.386| 0.302| 3.874| 0.104| 3.494| 0.060| 3.447| 0.013| 3.080| 0.020| 2.09 | 01364+5927 | 13   |
| 009 | 49  | W And     | 021733.26   | +441818.2    | 1.591| 0.248| 0.505| 0.198| 0.130| 0.184| 0.895| ...  | 0.986| 0.006| -1.029| 0.090| -1.667| 0.006| 0.27 | 02143+4404 | 4    |
| 010 | 57  | BI And    | 022554.40   | +380726.4    | 3.498| 0.268| 2.433| 0.192| 1.917| 0.244| 2.899| 0.023| 2.403| 0.090| 1.605| 0.008| 1.214| 0.008| 0.36 | 02228+3753 | 13   |

(This table is available in its entirety in machine-readable form.)
3. 2MASS, WISE, and IRAS Two-color Diagrams for Intrinsic S-type Stars and Extrinsic S-type Stars

In order to reveal the infrared properties of intrinsic S-type stars and extrinsic S-type stars, several two-color diagrams using the 2MASS, WISE, and IRAS photometry data from Tables 1 and 2 are constructed. It is noted that in some previous papers the 2MASS JHK data are often combined with IRAS data, and even the visual data and MSX data, to construct the two-color diagrams and obtain the results. However, many S-type stars are Mira-type variables or semiregular variables. In order to avoid the errors due to observational data used in different time, we use only the data of one mission in each of the two-color diagrams for the analysis in this paper.

Although, as showing in Section 1 of this paper, some authors already used 2MASS and IRAS data to discuss infrared properties of intrinsic S-type stars and extrinsic S-type stars, but samples in this paper are larger to get more convincing results.

In addition, in order to show infrared properties clearly, the blackbody distributions and the power-law distributions are also shown.
also presented in these two-color diagrams using the method from Chen et al. (2016).

### 3.1. 2MASS Two-color Diagram

Taking 2MASS data from Tables 1 and 2, the $(J-H)$ versus $(H-K)$ diagram can be shown in Figure 1 for known intrinsic S-type stars and extrinsic S-type stars. From Figure 1 we find that: (1) almost all sources are located around or in the upper left of the blackbody line, indicative of the thermal radiations from the stellar photosphere and/or dust in circumstellar envelopes; and (2) statistically, intrinsic S-type stars have much larger infrared excess than extrinsic S-type stars. In the region of $H-K > 0.6$ and $J-H > 1.2$ no extrinsic S-type stars appear.

### 3.2. WISE Two-color Diagrams

Taking WISE data from Tables 1 and 2 the one of WISE two-color diagram, the $(W2-W3)$ versus $(W1-W2)$ diagram can be plotted in Figure 2 for known intrinsic S-type stars and extrinsic S-type stars. From Figure 2 it is seen that: (1) the majority of both types of sources are located around or in the bottom right region of the blackbody line, indicative of dust thermal radiations from circumstellar envelopes; (2) the most of extrinsic S-type stars are distributed in the region around $W2-W3 = 0$ indicating no infrared excess in this color; (3) it is unexpected that some sources are located in the left region of the power-law line with the high temperate; (4) statistically, intrinsic S-type stars have much larger infrared excesses than...
Table 3

| CSS  | \( J \) | \( H \) | \( K \) | \( Av \) | \( (H–K) \) | \( (J–H) \) |
|------|--------|--------|--------|--------|---------|---------|
| CSS2 01 | 8.430 | 7.040 | 6.396 | 0.16 | 0.633 | 1.373 |
| CSS2 02 | 7.799 | 6.102 | 5.196 | 0.16 | 0.895 | 1.680 |
| CSS2 03 | 8.207 | 6.311 | 6.292 | 0.16 | 0.608 | 1.279 |
| CSS2 06 | 7.610 | 6.306 | 5.745 | 0.17 | 0.550 | 1.286 |
| CSS2 07 | 7.508 | 6.167 | 5.680 | 0.17 | 0.476 | 1.323 |
| CSS2 08 | 8.113 | 6.555 | 5.743 | 0.17 | 0.801 | 1.540 |
| CSS2 09 | 6.365 | 4.852 | 4.200 | 0.17 | 0.641 | 1.495 |
| CSS2 10 | 7.704 | 6.391 | 5.832 | 0.18 | 0.547 | 1.295 |
| CSS2 11 | 8.020 | 6.428 | 5.678 | 0.19 | 0.808 | 1.572 |
| CSS2 12 | 7.145 | 5.762 | 5.147 | 0.26 | 0.598 | 1.356 |
| CSS2 16 | 7.401 | 6.000 | 5.378 | 0.26 | 0.605 | 1.374 |
| CSS2 17 | 7.901 | 6.510 | 5.902 | 0.32 | 0.587 | 1.358 |
| CSS2 18 | 8.757 | 6.470 | 5.892 | 0.53 | 0.544 | 1.333 |
| CSS2 22 | 8.386 | 6.350 | 5.149 | 0.68 | 1.158 | 1.968 |
| CSS2 23 | 8.056 | 6.570 | 5.943 | 0.65 | 0.585 | 1.421 |
| CSS2 24 | 5.838 | 4.632 | 3.844 | 0.73 | 0.741 | 1.133 |
| CSS2 29 | 5.367 | 4.254 | 3.486 | 0.62 | 0.631 | 1.250 |
| CSS2 30 | 7.896 | 6.049 | 6.134 | 0.20 | 0.586 | 1.231 |
| CSS2 31 | 7.783 | 6.213 | 5.217 | 0.26 | 0.853 | 1.345 |
| CSS2 32 | 6.486 | 4.934 | 3.989 | 1.51 | 0.849 | 1.401 |
| CSS2 33 | 7.456 | 5.827 | 5.042 | 1.35 | 0.699 | 1.494 |
| CSS2 34 | 8.012 | 6.837 | 5.521 | 1.22 | 0.788 | 1.503 |
| CSS2 35 | 7.894 | 6.044 | 5.152 | 1.07 | 0.824 | 1.743 |
| CSS2 37 | 7.326 | 5.745 | 4.993 | 0.98 | 0.690 | 1.483 |
| CSS2 38 | 7.372 | 5.985 | 5.348 | 0.93 | 0.578 | 1.294 |
| CSS2 39 | 7.269 | 5.528 | 4.697 | 0.93 | 0.772 | 1.648 |
| CSS2 40 | 8.644 | 7.132 | 6.296 | 0.80 | 0.785 | 1.431 |
| CSS2 41 | 6.045 | 4.605 | 3.933 | 0.85 | 0.618 | 1.355 |
| CSS2 42 | 7.255 | 5.832 | 4.970 | 0.75 | 0.814 | 1.348 |
| CSS2 43 | 7.501 | 6.069 | 5.381 | 0.72 | 0.642 | 1.360 |
| CSS2 48 | 6.762 | 6.201 | 5.566 | 0.57 | 0.598 | 1.414 |
| CSS2 50 | 7.088 | 5.775 | 5.120 | 0.53 | 0.621 | 1.259 |
| CSS2 52 | 8.135 | 6.332 | 5.490 | 0.49 | 0.811 | 1.754 |
| CSS2 53 | 6.863 | 5.212 | 4.397 | 0.44 | 0.786 | 1.609 |
| CSS2 55 | 6.902 | 5.295 | 4.517 | 0.40 | 0.752 | 1.566 |
| CSS2 56 | 7.234 | 5.716 | 4.985 | 0.40 | 0.705 | 1.477 |
| CSS2 57 | 7.458 | 5.822 | 5.050 | 0.41 | 0.745 | 1.594 |
| CSS2 58 | 7.597 | 5.612 | 4.580 | 0.37 | 1.008 | 1.948 |
| CSS2 59 | 7.662 | 5.800 | 4.986 | 0.35 | 0.791 | 1.826 |
| CSS2 61 | 7.687 | 6.097 | 5.352 | 0.33 | 0.723 | 1.556 |
| CSS2 62 | 7.085 | 5.481 | 4.690 | 0.32 | 0.770 | 1.571 |
| CSS2 63 | 6.886 | 5.524 | 4.846 | 0.32 | 0.657 | 1.329 |
| CSS2 64 | 7.898 | 6.541 | 5.911 | 0.30 | 0.610 | 1.326 |
| CSS2 67 | 6.880 | 5.590 | 5.073 | 0.25 | 0.500 | 1.264 |
| CSS2 68 | 7.193 | 5.830 | 5.225 | 0.25 | 0.588 | 1.337 |
| CSS2 72 | 7.699 | 6.320 | 5.766 | 0.20 | 0.540 | 1.358 |
| CSS2 73 | 8.286 | 6.787 | 5.944 | 0.17 | 0.832 | 1.481 |
| CSS2 74 | 9.152 | 7.507 | 6.810 | 0.17 | 0.686 | 1.627 |

(Continued)
extrinsic S-type stars; and (5) in the region of W2–W3 > 1.0 all sources are intrinsic S-type stars.

Another WISE two-color diagram, the (W3–W4) versus (W2–W3) diagram can be plotted in Figure 3 for known intrinsic S-type stars and extrinsic S-type stars. It can be seen from Figure 3 that: (1) it is unexpected that over half of the sources are located around the power-law line; (2) statistically, intrinsic S-type stars have much larger infrared excess than extrinsic S-type stars either in the [12]–[25] color and the [25]–[60] color, and extrinsic S-type stars are mainly distributed in a narrow region around [12]–[25] = 0.1 showing no infrared excess in this color; and (3) in the regions of [12]–[25] > 0.35 and [25]–[60] > 0.8 all of the sources are intrinsic S-type stars.

In summary, statistically, in the 1–60 μm wavelength region intrinsic S-type stars in the AGB phase have much larger infrared excesses than extrinsic S-type stars in the RGB/TP-AGB phase due to thick dust circumstellar envelopes for formers, as expected. Another important result is that in the reddest color areas from all of the two-color diagrams above only intrinsic S-type stars can be found. In addition, in the wavelength longer than 5 μm some intrinsic S-stars and extrinsic S-stars have power-law distributions.

### 3.4. Discussion on the Power-law Distribution

It is seen from Figures 2–4 that some intrinsic and extrinsic S-stars have power-law distributions in the wavelength longer than 5 μm.

S-type stars often exhibit substantial mass loss through the dust-driven or pulsation-driven wind in the surrounding envelopes with gas and dust. The dust absorbs the stellar radiation and reradiate in the infrared (see, e.g., Hony et al. 2009). Therefore the possible reasons for power-law distributions for some S-type stars are as follows.

(1) One possibility is that it is caused by the disk-like structure of their dusty envelopes. The two typical S-type stars, π1 Gruis and RS Cnc, are proved to have the disk-like dusty envelopes with bipolar outflows (Hirano et al. 2005; Cruzalebes & Sacuto 2006 and Libert et al. 2010). Perhaps those S-type stars with power-law distributions in this paper have envelope structures similar to π1 Gruis and RS Cnc.

(2) Another possibility is that it is probably caused by the free–free/bound–free emissions in the stellar wind. Perhaps, besides the neutral gas, these stars may also have the ionized gases in their circumstellar envelopes to produce such emissions. Shetye et al. (2019) indeed detected the ionized material in some S-type stars.

### 4. Diagnosis for Finding Intrinsic S-type Stars

In order to further discuss classifications of S-type stars not listed in Tables 1 and 2, the 2MASS, WISE, and IRAS counterparts for all stars in CSS (Stephenson 1984) and CSS2 (Stephenson 1990) are cross-identified, and the Galactic extinctions are obtained for all 2MASS/WISE counterparts here according to the method in Section 2.
Figures 1–4 are together replotted in Figure 5. We can see that if we set out a line of $Y = -1.50X + 1.90$ in the 2MASS diagram of Figure 5, in the upper right region of this line only intrinsic S-type stars this line can be used to extract intrinsic S-type stars. Thus we can consider that for unclassified S-type stars this line can be used to extract intrinsic S-type stars. All unclassified S-type stars listed in CSS
are identified as new intrinsic S-type stars, which are listed in Table 3. The contents of Table 3 are: (1) the number in CSS or CSS2; (2) the $HJK$ magnitudes; (3) the derived Galactic extinction coefficient $A_v$; and (4) the de-reddening colors of $H-K$ and $J-H$.

In the WISE first and second diagrams it is clear that in the region with the $W2-W3$ color >1.0 only intrinsic S-type stars are found. Thus this is another diagnosis to extract intrinsic S-type stars from the unclassified samples in the CSS and CSS2. Finally, 35 sources in these catalogs are found as new intrinsic S-type stars that are listed in Table 4. The contents of Table 4 are: (1) the number in CSS or CSS2; (2) the magnitudes in $W2$ and $W3$; (3) the $A_v$ derived; and (4) the de-reddening color of $W2-W3$. In the table note the symbol “*” indicates the source already listed in Table 3. It is seen that 35 sources are found to be new intrinsic S-type stars and 25 sources are already listed in Table 3.

If we draw a line of $Y = -3X + 1.4$ in the IRAS diagram of Figure 5, it can be seen that only intrinsic S-type stars are located in the right region of this line. Thus we can consider that for unclassified S-type stars this line can be used to extract intrinsic S-type stars. All unclassified S-type stars listed in CSS (Stephenson 1984) and CSS2 (Stephenson 1990) are tested in this diagram. Finally, 57 sources in these catalogs are identified as new intrinsic S-type stars, which are listed in Table 5. The contents in Table 5 are: (1) the number in CSS or CSS2; (2) the IRAS name; (3) the fluxes in $12, 25$, and $60 \mu$m in Jy; and (4) the $[12]-[25]$ and $[25]-[60]$ colors. In the table notes the symbol “*” indicates the source already listed in Table 3 and the symbol “#” indicates the source already listed in Table 4. It can be seen that 57 sources are found to be new intrinsic S-type stars, and among them 28 sources are already listed in Tables 3 and 12 sources are already listed in Table 4.

It is seen from Tables 3–5 that 172 sources in total are newly identified intrinsic S-type stars in this paper. It can be seen that the number of previously known intrinsic S-type stars is 190 from Table 2, and the number of new intrinsic S-type stars found in this paper is 172. It means that the number of known intrinsic S-type stars is almost double after this paper.

5. Summary

We have collected 151 certain extrinsic S-type stars and 190 certain intrinsic S-type stars to study their infrared properties using several two-color diagrams from 2MASS, WISE, and IRAS data in this paper.

The results in this paper reveal that, statistically, intrinsic S-type stars have larger infrared excesses than extrinsic S-type stars in the wavelength range of 1–60 $\mu$m due to more thick dust circumstellar envelopes. It is found that in all two-color diagrams, only intrinsic S-type stars occupy the reddest color areas. This result can be used as a diagnostic to extract intrinsic S-type stars. Finally, 172 new intrinsic S-type stars are presented. This makes the number of known intrinsic S-type stars almost double.

In addition, some intrinsic and extrinsic S stars have power-law distributions in the two-color diagrams in the wavelength longer than 5 $\mu$m. The possible reasons for this are also discussed.

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