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Near-infrared observations of candidate extrinsic S stars

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Abstract. Photometric observations in the near infrared for 161 S stars, including 18 Tc-rich (intrinsic) stars, 19 Tc-deficient (extrinsic) ones and 124 candidates for Tc-deficient S stars, are presented in this paper. Based on some further investigations into the infrared properties of both Tc-rich and Tc-deficient S stars, 104 candidates are identified as very likely Tc-deficient S stars. The large number of infrared-selected Tc-deficient S stars provides a convenient way to study the physical properties and the evolutionary status of this species of S stars.

Key words. stars: AGB and post-AGB – stars: evolution – stars: circumstellar matter – infrared: stars

1. Introduction

Recent research suggests that two categories of S stars exist, as proposed early by Iben & Renzini (1983):

(1) intrinsic S stars, indeed lying on the asymptotic giant branch (AGB) phase of stellar evolution, following the usual M–S–C evolution sequence, and, as a defining characteristic, showing Tc lines in their optical spectra: also called as Tc-rich S stars or S stars with Tc;
(2) extrinsic S stars, populating the first red giant branch (RGB), belonging to white dwarf (WD) containing binary systems, having enhanced *s*-process elements at the stellar surface as the result of mass transfer from an AGB star (now the WD) to a less evolved companion (now the "S star"), but having no Tc: referred to as Tc-deficient S stars or S stars without Tc.

The existence of S stars without Tc was first discussed by Scalo & Miller (1981) on the basis of the data of Little-Marenin & Little (1979), and has been supported by several further observations (Little et al. 1987; Smith & Lambert 1988, 1990; Jorissen et al. 1993; and recently Van Eck & Jorissen 1999). However, it is generally difficult to detect the Tc lines directly since these lines are very weak and lie in a spectral region crowded with many other lines. Of the some 1500 S stars known in the Galaxy only a tiny minority has been observed for the presence of Tc. Thus we have to find other (indirect) approaches to distinguish Tc-deficient S stars from Tc-rich ones.

Although the periodic radial-velocity variation attributable to the orbital motion of a binary system has been seen for some Tc-deficient stars from Jorissen & Mayor (1988, 1992), Brown et al. (1990), and more recently from Udry et al. (1998) and Carquillat et al. (1998), the determination of radial velocity variation is limited by the long orbital periods (on a scale of years). Another approach is to observe the He I 10830 Å triplet in the spectra of Tc-deficient stars (Brown et al. 1990). The He I line is lacking in normal, single giants later than K, and the WD companion is supposed to be an essential prerequisite for the He I line production in Tc-deficient S stars. Unfortunately, such a prominent feature is undetectable in the vast majority of the spectra of Tc-deficient stars for the triplet almost reaching the cut-off wavelength of the response curve of current CCD cameras. Moreover, excess ultraviolet emission arising from the WD should be visible for Tc-deficient S stars (Johnson et al. 1990, 1993), but the data in the ultraviolet have so far been obtained only from IUE for very few stars. Therefore, it seems that an additional approach, namely studying the infrared colors, may help identify the two categories of S stars for a sample with many stars.

Since the Tc-rich S stars are luminous, cool AGB stars and surrounded by a circumstellar shell, while the Tc-deficient ones are supposed to be less luminous, hot and less evolved, the infrared characteristics of the two classes may be very different (Jura 1986; Groenewegen 1993; Jorissen et al. 1993; Jorissen & Knapp 1998; Van Eck & Jorissen 2000). In a previous work (Chen et al. 1998, hereafter Paper I) we studied in detail the infrared properties of both categories of S stars on the basis of our near infrared photometry and the IRAS data for 24 known Tc-rich and 20 known Tc-deficient S stars: a series of infrared two-color diagrams were presented, the energy distributions were investigated and the IRAS LRS spectra were discussed.

As work continued from Paper I, we report in this paper the *JHK* photometric observations for a large sample

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of candidates for Tc-deficient S stars, together with the discussion of some infrared characteristics so as to identify new Tc-deficient S stars.

2. Sample

All candidates for Tc-deficient S stars studied here are selected from *A catalogue of associations between IRAS sources and S stars* (Chen et al. 1995, hereafter CGJ) on the following criteria:

(1) $V \lesssim 11\overset{m}{.}5$;
(2) $-20° < \delta < 64°$;
(3) the LRS classification is in groups S or F, or no LRS classification exists; and
(4) $\alpha_{12} \geqq 2.70$, or there is no α_{12} value in the catalog [that means a good quality 25 μm flux (*Flag* > 2) not available in the *IRAS Point Source Catalog* (JISWG 1988, hereafter PSC)]. Here, α_{12} is the spectral slope between the 12 and 25 μm bands, defined as

$$\alpha_{12} = \log(25F_{12}/12F_{25})/\log(25/12). \quad (1)$$

The F_{12} and F_{25} are fluxes in Jy at 12 and 25 μm respectively.

The second criterion is called for by the condition and location of the telescope used. The third one comes from the conclusion of Paper I that LRS classification E is a good indicator of the AGB nature of a star, while candidates for Tc-deficient S stars should be searched for among those in groups S and F. This claim has also been proposed by Chen & Kwok (1993) and it is consistent with the analysis of Groenewegen (1993).

Tc-deficient S stars have relatively warm photospheres but have little or no circumstellar material. It should be expected that the fluxes in IRAS bands come from hot stellar photospheres and can thus be represented by the Rayleigh-Jeans tail of the spectra, that is, both spectral indices α_{12} and α_{23} for these stars are near 3 (α_{23} is the 25 to 60 μm spectral slope and expressed in a similar form to that of α_{12}). Out of the S stars whose α_{12} were given by CGJ, about 30% have $\alpha_{12} \geqq 2.70$. These spectra with a slope close to the Rayleigh-Jeans value are indicative of color temperatures in excess of 2000 K (*IRAS Explanatory Supplement*, JISWG 1988). Therefore, we shall focus our discussion in this paper on the sources with $\alpha_{12} \geqq 2.70$ so that the fourth criterion is obtained.

The critical α_{12} of 2.70 can, in fact, be deduced from Table 1 and Fig. 1. In Table 1 the α_{12} value of the S stars which are believed to be either Tc-rich or Tc-deficient are listed. All stars studied by Jorissen et al. (1993) are involved and several stars from Groenewegen (1993) are supplemented. The α_{12} value is taken from CGJ or, if not available, computed in this work. The number in *General Catalogue of Galactic S Stars* (Stephenson 1984, hereafter GCGSS), the IRAS name and the LRS classification are also listed. In Fig. 1 the histograms of α_{12} for Tc-rich and Tc-deficient stars are presented. From Table 1 and Fig. 1 it is obvious that except for S231 = DY Gem and S233 = BD + 2°1307 which will be discussed in Sect. 4.1, all Tc-deficient S stars have α_{12} either greater than or very close to 2.70, whereas most Tc-rich ones (74% of 39) have α_{12} less than 2.70 and the average for this kind of stars is only 2.48.

Thus, 124 candidates are selected from CGJ.

In addition, 18 known Tc-rich and 19 known Tc-deficient S stars are also included in our observational list, as most of them were not studied in Paper I. The final sample consists of 161 S stars which are observed in *JHK* bands and investigated on their infrared properties.

Table 1. α_{12} values of the S stars whose Tc contents are well known.
a. Tc-deficient S stars.

GCGSS	IRAS	α_{12}	LRS
3	00051 − 6235	2.86	
22	01025 + 1855	2.80	
26	01113 + 2815	2.83	F
39	01309 − 7913	3.41	
45	01515 + 2138	3.02	
79	03377 + 6303	2.81	S(18)
87	04030 + 2435	2.93	
96	04248 + 2214	3.24	
104	04374 − 3033	2.80	
106	04470 + 7955	/	
133	05199 − 0842	2.88	S(16)
156	05404 + 0503	/	
231	06331 + 1415	2.00	F(42)
233	06336 + 0200	2.36	
260	06457 + 0535	2.87	
382	07392 + 1419	2.84	S(18)
494	08188 + 1726	2.94	I
566	08529 + 0620	/	
DE Leo	10226 + 0902	2.88	S(01)
712	10538 − 1033	/	
722	11046 + 6838	2.82	
829	13421 − 0316	/	
926	16205 + 5659	2.80	
937	16418 − 1359	2.87	S(19)
938	16425 − 1902	2.93	S(31)
981	17200 + 2351	2.72	
1023	18058 − 3658	2.67	
1031	18128 + 1614	2.78	
1092	18567 + 2353	/	
V1743 Peg	19323 + 4909	2.80	S(17)
1173	19540 − 1829	/	
1178	19581 + 0113	2.68	
1192	20055 + 3625	2.90	
1194	20076 + 3331	2.76	
1201	20152 + 3124	2.95	
1209	20203 + 2319	2.67	
1301	22345 − 1031	2.80	
1304	22415 + 3339	2.77	
1322	23070 + 0824	2.90	S(18)
1334	23272 + 2859	/	

Table 1. continued.
b. Tc-rich S stars.

GCGSS	IRAS	α_{12}	LRS
8	00192 − 2020	2.73	F(16)
9	00213 + 3817	1.91	E
12	00435 + 4758	2.66	S(01)
49	02143 + 4404	2.15	E(22)
89	04123 + 2357	2.65	S
103	04352 + 6602	2.69	S(17)
114	04497 + 1410	2.88	S(18)
116	04543 + 4829	2.51	F
149	05374 + 3153	1.87	E(43)
307	07043 + 2246	2.44	F(16)
312	07095 + 6853	2.19	F
V Gem	07203 + 1311	2.40	F
347	07245 + 4605	1.87	E(23)
403	07462 + 2351	2.77	
411	07475 − 1852	2.64	
416	07499 − 0459	2.61	
422	07507 − 1129	2.83	I
589	09076 + 3110	2.13	E(22)
HR 4647	12106 − 3350	2.52	S
803	12417 + 6121	2.51	
866	14500 − 4624	2.71	I
903	15492 + 4837	1.98	E(41)
S Her	16496 + 1501	2.49	S(17)
OP Her	17553 + 4521	2.57	S(17)
1053	18288 + 3612	2.77	
1070	18395 + 0646	2.77	
1099	19008 + 1210	2.61	S
1117	19133 − 1703	2.41	F
1150	19354 + 5005	1.95	E(22)
1165	19486 + 3247	2.77	E
1188	20026 + 3640	2.28	S(31)
1193	20062 + 0451	2.67	
1195	20100 − 6225	2.76	S(18)
1198	20120 + 1651	2.50	
1226	20303 + 1716	2.58	
1254	[a]		
HR 8062	[a]		
1292	22159 − 2109	2.34	F
1294	22196 − 4612	2.00	E(42)
1315	22521 + 1640	2.84	S
1346	23595 − 1457	2.65	F(16)

[a] In a region of the sky not surveyed by IRAS.

3. Observation and data reduction

Near infrared observations were made from Dec. 1995 to Oct. 1997 by using the 1.26-m infrared telescope at the Xinglong Station, Beijing Astronomical Observatory, China. The photometric system and the standard stars used are the same as those described in Paper I. A diaphragm of 16″ was used throughout. For each night the atmospheric extinction coefficients at *JHK* bands were obtained by measuring a standard star at different zenith distances. In order to minimize the influence of local changes in atmospheric conditions, most of the observations were made near the zenith and, typically, the airmass difference between the program star and the standard one was less than 0.1. The photometric accuracies derived from the measurements of standard stars are $0\overset{m}{.}03$–$0\overset{m}{.}07$.

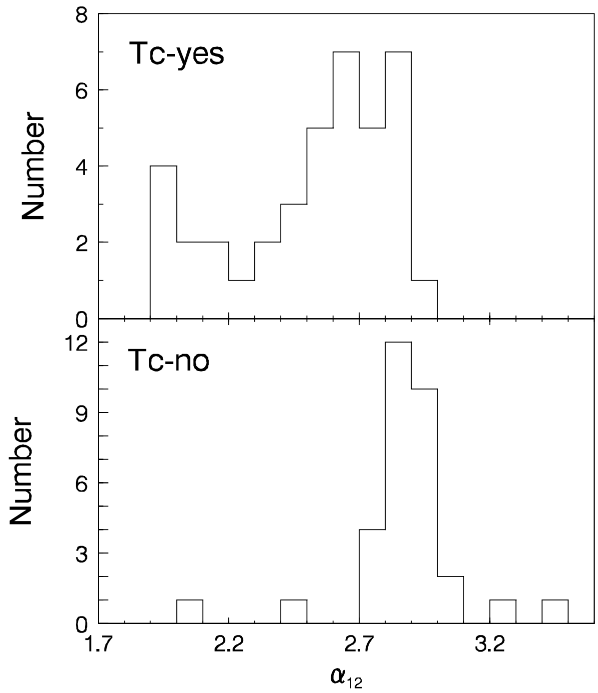

Fig. 1. Histogram of the 12 to 25 μm spectral slope for known Tc-rich and Tc-deficient S stars.

To estimate the interstellar reddening, van Herk's (1965) interstellar extinction relation

$$A_V = 0.14 \csc|b|[1 - \exp(-10d \sin|b|)], \quad (2)$$

where b is the galactic latitude and d the distance in kpc, and Rieke & Lebofsky's (1985) reddening law

$$A_J = 0.282A_V\,, \quad A_H = 0.175A_V\,, \quad A_K = 0.112A_V \quad (3)$$

have been used. Although the HIPPARCOS mission has provided trigonometrical parallaxes for 62 S stars (Van Eck et al. 1998), only 16 stars among them are in common with those observed here, and what is more, only 8 stars have useful parallaxes (i.e., the ratio of the standard error of annual parallax to the parallax itself is between 0 and 1.0). Therefore, an average absolute K magnitude $M_K = -8.5$ (Feast et al. 1976) would be assumed for all observed S stars, from which d and A_V may be estimated by means of an iterative method. Then the interstellar reddening was corrected for *JHK* magnitudes.

The observational results with observing dates are listed respectively in Table 2 for known Tc-deficient and Tc-rich S stars, and in Table 3 for the candidates of Tc-deficient stars. In the tables, the "Name" column lists the GCGSS number (preceded with a capital "S") or the

Table 2. Observed S stars whose Tc contents have been well known.
a. Tc-deficient S stars.

Name	IRAS	Date	$V(B)$	J	H	K	F_{12}	F_{25}	F_{60}	F_{100}	LRS	CIO
S45	01515 + 2138	951227	8.3	5.23	4.37	4.24	1.041	0.236	/	/		***
S87	04030 + 2435	951227	8.8	4.08	3.32	3.13	3.008	0.731	/	/		vvK
		960318		4.79	3.72	3.19						
S96	04248 + 2214	951227	9.6	4.41	3.69	3.44	2.537	0.491	/	/		vHK
		960318		4.63	3.74	3.57						
S156	05404 + 0503	951227	9.1	5.51	4.71	4.49	0.910	/	/	4.660		JHK
		960318		5.52	4.62	4.52						
S233	06336 + 0200	960324	(10.5)	4.68	4.15	4.03	0.921	0.340	/	/		vvv
S494	08188 + 1726	960314	8.9	4.39	3.59	3.28	8.412	2.021	/	/	I	JHK
S566	08529 + 0620	960314	9.0	5.27	4.45	4.29	0.974	/	/	/		***
S712	10538 − 1033	960318	(10.6)	5.85	4.90	4.69	0.878	/	/	/		***
S829	13421 − 0316	960314	(9.4)	5.18	4.32	4.15	1.006	/	/	/		***
S926	16205 + 5659	960314	6.6	4.18	3.48	3.34	2.378	0.635	/	/		***
S981	17200 + 2351	960314	9.4	5.53	4.90	4.65	0.688	0.195	/	/		***
S1031	18128 + 1614	960324	7.4	3.22	2.49	2.30	5.591	1.514	/	/		**K
S1092	18567 + 2353	960318	9.9	5.96	5.52	5.01	0.542	/	/	/		***
S1173	19540 − 1829	971023	(10.1)	4.86	4.24	3.98	1.274	/	/	/		***
S1201	20152 + 3124	960324	8.6	3.70	2.99	2.82	2.876	0.687	/	22.89		***
S1209	20203 + 2319	971023	9.4	4.88	4.24	3.96	1.048	0.307	/	/		***
S1334	23272 + 2859	951227	9.3	6.26	5.39	5.24	0.507	/	/	/		***
DE Leo	10226 + 0902	960314	(5.6)	2.03	1.53	1.29	14.29	3.583	0.794	0.755	S(01)	v*K
V1743 Peg	19323 + 4909	960324	(5.9)	1.62	0.87	0.72	26.02	6.946	1.022	/	S(17)	J*K

b. Tc-rich S stars.

Name	IRAS	Date	$V(B)$	J	H	K	F_{12}	F_{25}	F_{60}	F_{100}	LRS	CIO
S9	00213 + 3817	971021	6.8	2.66	1.29	0.65	327.0	167.7	24.16	10.37	E	vvv
S49	02143 + 4404	971021	10.5	1.22	0.47	0.00	167.4	72.14	13.45	5.606	E(22)	vvv
S89	04123 + 2357	951227	6.9	2.07	1.23	0.95	24.43	7.298	2.631	2.608	S	**K
S103	04352 + 6602	970102	8.2	1.90	1.25	1.04	41.29	11.91	3.632	2.577	S(17)	Jvv
S114	04497 + 1410	951227	4.8	0.44	−0.30	−0.54	85.35	21.43	4.569	3.788	S(18)	**K
S416	07499 − 0459	960324	(10.5)	4.36	3.67	3.43	1.905	0.584	/	/		***
S589	09076 + 3110	960314	7.0	−0.58	−1.33	−1.62	479.9	208.7	32.58	10.10	E(22)	JHK
S903	15492 + 4837	960314	7.2	0.49	−0.18	−0.61	199.3	97.09	16.70	5.973	E(41)	**K
S1099	19008 + 1210	960324	8.5	2.75	2.15	2.01	10.95	3.360	0.808	/	S	vHK
S1117	19133 − 1703	971023	11.5	1.87	1.21	0.87	40.29	14.30	4.043	2.845	F	vvv
S1193	20062 + 0451	971023	9.1	4.63	3.90	3.67	1.781	0.522	0.547	/		***
S1198	20120 + 1651	971023	9.1	3.34	2.66	2.58	6.196	2.067	/	/		**K
S1346	23595 − 1457	970102	(12.4)	2.77	2.36	2.22	13.31	3.964	0.725	/	F(16)	vvv
V Gem	07203 + 1311	960324	12.2	3.32	2.63	2.48	9.241	3.313	0.362	/	F	vvv
S Her	16496 + 1501	960324	8.7	2.59	1.88	1.55	34.32	11.46	1.916	0.780	S(17)	Jvv
OP Her	17553 + 4521	960324	(6.4)	1.29	0.39	0.28	54.13	17.12	3.349	2.317	S(17)	J*K
S1254	[a]	971023	7.1	2.01	1.38	1.07						**K
HR 8062	[a]	971023	5.8	1.58	1.02	0.72						**K

[a] In a region of the sky not surveyed by IRAS.

number in the Stephenson's (1990) catalog for new and relatively faint S stars (preceded with "Sf") or the variable star name or the HR number. The IRAS associations are taken from CGJ for the great majority of stars and from Jorissen et al. (1993) for several stars not included in GCGSS and, in the case of V Gem, from the *IRAS LRS Letter Classification Lists* (Kwok et al. 1997, hereafter LRSLC). The IRAS fluxes (in Jy) at 12, 25, 60 and 100 μm bands are from PSC and only good quality ones are listed. From LRSLC and the *IRAS Atlas of Low-Resolution Spectra* (JISWG 1986) both the LRS classification in letter codes defined by Volk & Cohen (1989) and that in the usual two-digit codes are presented. In the forth column of Tables 2 and 3, the $V(B)$ magnitudes taken from the *Hubble Space Telescope Guide Star Catalog* (1992) or the GCGSS are given for most stars, but the I magnitudes from Stephenson (1990) are given for his faint S stars. In the last column (referred to as "CIO") whether near infrared observations appear in the *Catalog of Infrared Observations* (Gezari et al. 1993,

Table 3. Observed candidates for Tc-deficient S stars.

Name	IRAS	Date	$V(B)$	J	H	K	F_{12}	F_{25}	F_{60}	F_{100}	LRS	Tc	CIO
S10	00300 + 6342	951227	11.6	5.09	4.69	4.47	0.657	/	/	/		n:	***
S32	01229 + 2108	970102	10.4	6.25	5.55	5.18	0.770	/	/	/			***
S42	01441 + 5127	951227	11.3	6.48	5.83	5.58	0.295	/	/	/		n:	***
S47	02048 + 6208	951227	11.6	5.27	4.90	4.86	0.449	/	/	/		n:	***
S52	02151 + 3130	951227	9.1	5.42	4.71	4.43	1.670	0.454	/	/			vvv
S57	02228 + 3753	951227	10.2	3.04	2.35	2.08	10.27	2.807	0.643	0.964	S(01)	n	**K
S76	03327 + 6403	960318	12.0	5.81	4.70	4.48	0.992	/	/	/		n:	***
		970101		5.84	4.72	4.54							
S78	03361 + 5056	951227	10.5	4.18	3.56	3.37	2.217	0.599	/	/		n	***
S80	03406 + 2216	951227	9.1	4.86	4.06	3.87	1.645	0.423	/	/		n	***
		960318		4.86	4.05	3.77							
S81	03433 + 5254	951227	10.2	3.75	3.00	2.88	3.915	0.983	/	/		n	**K
S83	03482 + 0645	951227	10.6	6.44	5.58	5.27	0.526	/	/	/		n:	***
S86	03572 + 6133	951227	11.0	5.97	5.14	4.95	0.691	/	/	/		n:	***
S94	04218 − 0238	951227	(10.5)	5.51	4.92	4.65	0.831	0.211	/	0.675		n	vvv
		960324		5.54	4.72	4.57							
S101	04323 + 4040	951227	11.6	6.46	5.56	5.41	0.378	/	/	/		n:	***
S102	04328 + 1235	951227	10.0	3.81	3.13	2.68	5.394	1.534	/	/		n	JHK
S105	04414 + 4616	951226	9.7	5.27	5.31	5.30	0.390	/	/	/		n:	***
S111	04484 + 3958	951227	9.7	5.14	4.78	4.58	0.681	/	/	/		n:	***
S115	04506 + 3159	951227	11.4	6.21	5.48	5.23	0.463	/	/	/		n:	***
S124	05087 + 4649	951227	10.9	5.67	5.01	4.84	0.631	/	/	/		n:	***
S132	05190 + 4831	951227	11.4	5.61	4.93	4.61	0.731	/	/	/		n:	***
S138	05225 + 3221	951227	11.1	5.90	5.43	5.45	0.293	/	/	/		n:	***
S142	05289 + 4056	951227	12.2	5.72	5.36	5.03	0.533	/	/	/		n:	***
S152	05389 + 5211	951227	8.8	4.85	4.01	3.85	2.134	0.529	/	/		n	***
		960324		4.95	4.04	3.82							
S153	05390 + 1831	960318	8.9	3.67	2.76	2.58	5.939	1.674	/	/		n	JHK
S158	05411 + 0736	951227	9.7	4.91	4.15	4.11	1.477	0.361	/	/		n	***
		960318		4.73	4.05	3.88							
S161	05446 + 0239	951227	10.8	5.65	4.98	4.67	0.790	/	0.648	/		n:	***
S162	05449 − 0423	960318	(12.4)	5.47	4.43	4.26	1.044	0.286	/	/		n	***
S163	05465 + 0641	951227	10.8	6.01	5.17	4.92	0.795	/	/	/			***
S165	05492 + 2549	951227	10.3	3.70	3.07	2.88	3.591	0.934	/	/		n	***
S167	05484 − 1708	960318	(9.9)	4.79	4.13	4.03	1.160	0.272	/	/		n	***
S171	05519 + 4618	951227	11.0	6.75	5.52	5.18	0.354	/	/	/		n:	***
S176	05567 − 1052	960318	(11.4)	3.32	2.40	2.24	6.706	1.734	0.416	/		n	**K
S181	06001 + 3138	960318	9.6	4.17	3.67	3.19	2.659	0.754	/	/		n	vvv
S183	06018 + 2746	951227	11.3	5.46	5.18	4.95	0.619	/	/	/		n:	***
S188	06052 + 2807	951227	11.3	6.15	5.63	5.47	0.290	/	/	/		n:	***
S198	06105 + 0127	951227	(11.6)	5.99	5.30	5.12	0.450	/	/	/		n:	***
S207	06146 + 0200	951227	(11.8)	5.17	4.79	4.45	1.047	/	/	/		n:	***
S212	06197 + 0327	960324	8.1	2.67	1.89	1.51	16.97	4.732	1.646	3.407	S(18)	n	vvv
S213	06197 − 0751	960324	(13.2)	5.62	4.98	4.65	0.856	0.193	/	/		n	***
S214	06208 + 2120	951227	11.0	5.35	4.67	4.50	0.807	/	/	/		n:	***
S219	06241 + 1555	951227	9.2	4.12	3.70	3.27	2.277	0.629	/	/		n	vHK
		960324		4.02	3.44	3.32							
S223	06298 − 1338	970315	(12.4)	6.06	5.23	4.98	0.517	/	/	/		n:	***
S227	06325 + 5227	960318	10.3	5.47	4.69	4.45	0.915	/	/	/		n:	***
S228	06322 + 3925	960318	10.7	6.18	5.52	5.31	0.410	/	/	/		n:	***
S239	06368 + 2541	951227	10.9	6.21	5.61	5.38	0.302	/	/	/		n:	***
S247	06402 + 2548	951227	8.5	5.53	4.95	4.86	0.650	/	/	/		n:	vvv
S262	06462 + 0659	960324	11.5	4.92	4.27	4.12	1.025	/	/	/		n:	***
S266	06477 + 2905	951227	11.4	6.96	6.11	5.91	0.728	/	/	/			***
S270	06509 + 2612	951227	10.4	5.88	5.02	4.42	1.428	/	/	/			***

hereafter CIO) is reflected by a set of 3 symbols for J, H and K bands respectively. The symbol "$*$" denotes that there is no observation appearing in CIO catalog, a "J" or an "H" or a "K" indicates the CIO magnitudes at the corresponding band do not differ more than 0.2 from the value here, and a "v" shows a difference of more than 0.2 existing between the present measurement and one of the previous data in CIO for a corresponding band. Moreover, the column labelled "Tc" in Table 3 stands for the judgment on a star as a Tc-deficient S star according to the discussion in Sect. 4: a notation "n" means the star should be Tc-deficient as judged by the $(K-[12])-([12]-[25])$

Table 3. continued.

Name	IRAS	Date	$V(B)$	J	H	K	F_{12}	F_{25}	F_{60}	F_{100}	LRS	Tc	CIO
S288	06573 − 1412	970102	(11.2)	4.11	3.77	3.69	1.552	0.360	/	/		n	***
S290	06583 + 1929	960318	10.7	6.46	5.54	5.40	0.667	/	/	/			***
S306	07037 − 0346	960324	(11.6)	4.40	4.14	3.76	1.427	0.372	/	/		n	***
S311	07062 + 0314	960324	9.3	5.65	5.08	4.82	0.505	/	/	/		n:	***
S322	07116 − 0834	970101	(11.7)	5.12	4.65	4.70	0.420	/	/	/		n:	***
S332	07165 − 1109	970315	(10.5)	3.39	2.97	2.74	3.452	0.804	/	/		n	***
S334	07168 − 0037	960324	(12.8)	5.12	4.40	4.12	2.308	0.638	/	/			***
S335	07169 − 1122	970101	(9.6)	3.25	2.60	2.48	4.293	1.182	/	/		n	**v
		970315		3.27	2.57	2.36							
S362	07296 − 0924	960318	(13.5)	4.74	4.00	3.93	1.405	0.348	/	/		n	***
S363	07303 + 0153	960324	(12.7)	6.37	5.63	5.45	0.289	/	/	/		n:	***
S379	07363 − 1218	960324	(13.0)	5.75	5.33	5.11	0.358	/	/	/		n:	***
S413	07496 + 3444	960324	10.2	4.90	4.06	3.77	1.873	0.507	/	/		n	***
S418	07505 + 1754	960324	8.2	4.29	3.73	3.36	2.169	0.499	/	/		n	***
S454	08021 − 0255	960314	(12.2)	5.57	5.00	4.84	0.592	0.131	/	/		n	***
S471	08083 + 0817	960314	10.6	5.21	4.44	4.20	1.112	0.308	/	/		n	***
S836	13494 − 0313	960314	(10.6)	4.96	4.44	4.28	0.866	/	/	/		n:	***
S855	14251 − 0251	960314	(10.5)	5.56	4.77	4.56	0.793	/	/	/		n:	***
S908	15592 − 1109	960318	(10.5)	4.50	3.73	3.63	2.047	0.560	/	/		n	***
S959	17047 − 1303	960314	(11.5)	5.69	4.24	3.62	1.926	/	/	/		n:	***
S964	17112 + 0551	960314	8.1	4.58	3.63	3.36	2.256	0.538	/	/		n	**v
S968	17154 − 0510	960318	(12.7)	6.13	5.33	4.98	0.506	/	/	/		n:	***
S996	17379 − 0250	960318	(9.1)	3.75	2.88	2.71	3.673	0.941	/	/		n	**K
S1012	17563 − 1438	960318	10.9	5.32	4.34	4.18	0.856	/	/	/		n:	***
S1024	18052 + 0027	960318	10.8	6.43	5.54	5.51	0.436	/	/	/		n:	***
S1028	18087 + 2133	960318	9.1	6.27	5.34	5.11	0.391	/	/	/		n:	***
S1075	18439 + 2645	960318	8.9	6.66	5.70	5.60	0.318	/	/	/		n:	***
S1083	18508 − 1415	960318	11.1	5.66	4.86	4.65	1.369	/	/	/			***
S1097	18581 + 2636	960318	11.8	6.46	5.64	5.42	0.390	/	/	/		n:	***
S1105	19060 + 0225	960318	10.9	5.35	4.67	4.43	0.794	/	/	/		n:	***
S1118	19133 + 0032	960324	11.0	4.06	3.62	3.17	2.949	0.830	/	/		n	***
S1137	19232 + 4422	960324	(12.8)	6.25	5.40	5.16	0.965	0.244	/	/			***
S1143	19335 + 0358	960318	10.4v	4.99	4.18	3.72	2.498	0.619	/	/			***
S1144	19339 − 1128	971023	(10.6)	4.93	4.03	3.91	1.602	0.450	/	/		n	***
S1167	19497 + 4327	960324	10.1	4.19	3.37	3.12	3.421	0.963	/	/		n	***
S1169	19518 − 0803	971023	(11.1)	5.29	4.53	4.10	1.051	0.210	/	/		n?	***
S1179	19573 + 4826	960324	9.7	5.71	5.00	4.68	0.732	0.162	/	/		n	***
S1183	20004 + 1026	971023	9.5	5.63	5.22	5.06	0.395	/	/	/		n:	***
S1186	20019 + 1518	971023	10.7	5.73	5.32	5.23	0.371	/	/	/		n:	***
S1190	20051 − 0144	971023	(11.0)	3.97	3.28	2.89	3.844	1.142	/	/		n	**K
S1211	20213 + 0047	971023	(10.9)	2.41	1.64	1.31	21.92	7.133	1.295	/	S(17)	n?	vvv
S1219	20252 + 3623	971023	10.4	2.48	1.82	1.54	12.80	3.947	/	/	S(16)	n?	**K
S1225	20305 − 1546	971023	(10.5)	5.15	4.43	4.29	0.931	/	/	/		n:	***
S1227	20304 + 2430	971023	10.2	5.68	5.49	5.23	0.307	/	/	/		n:	***
S1232	20369 + 3742	971023	13.1	3.57	2.88	2.20	10.36	2.444	/	/	S		**K
S1235	20403 + 0830	971023	10.3v	5.46	5.12	4.93	0.618	/	/	/		n:	***
S1239	20455 + 3442	971023	10.4	5.21	4.86	4.73	0.425	/	/	/		n:	***
S1242	20488 + 2318	971021	9.8	5.98	5.14	4.98	0.481	/	/	/		n:	***
S1248	20506 + 3605	971021	9.8	5.49	4.89	4.77	0.522	/	/	/		n:	***
S1249	20512 + 5613	971021	10.8	6.04	5.43	5.25	0.361	/	/	/		n:	***
S1253	20550 + 2908	971021	9.9	4.41	3.59	3.26	2.898	0.824	/	/		n	***
S1257	20596 + 6136	971021	10.8	5.99	5.33	5.13	0.426	/	/	/		n:	***
S1267	21135 + 3133	971021	9.2	5.57	5.08	4.95	0.523	/	/	/		n:	***
S1274	21281 + 5103	971021	9.9	4.80	4.86	4.65	0.375	/	/	/		n:	***
S1277	21330 + 4037	971023	(11.7)	6.62	6.37	6.04	0.354	/	/	/			***

diagram; "n:" states that the judgment for Tc-deficiency is made only by the $K - [12]$ histogram due to the lack of the flux at 25 μm; and "n?" marks a star that has the proper $K - [12]$ color as a Tc-deficient S star but does not lie in the area populated by Tc-deficient stars in the $(K - [12]) - ([12] - [25])$ plot and should not be taken as a good candidate of Tc-deficient S stars.

Table 3. continued.

Name	IRAS	Date	$V(B)$	J	H	K	F_{12}	F_{25}	F_{60}	F_{100}	LRS	Tc	CIO
S1279	21345 + 4709	971021	10.9	4.73	4.01	3.70	1.758	0.485	/	/		n	***
S1281	21371 + 5153	971021	10.9	4.76	4.67	4.69	0.488	/	/	/		n:	***
S1285	21512 + 4602	971023	10.6	5.92	5.46	5.25	0.398	/	/	/		n:	***
S1286	21540 + 4806	971023	9.0	4.69	4.33	3.46	5.949	1.648	/	/			**v
S1290	22057 + 2925	951225	10.8	6.82	5.92	5.67	0.324	/	/	/		n:	***
S1308	22476 + 4047	970102	8.1	0.23	−.13	−.38	98.73	32.66	8.389	6.159	S(16)	n?	**K
S1309	22479 + 1737	970102	10.0	3.62	3.38	3.01	4.594	1.297	/	/		n	vHK
S1311	22489 + 0326	951225	9.0	6.58	5.82	5.80	0.410	/	/	/			***
S1313	22504 + 5009	951225	9.8	6.44	5.56	5.27	0.381	/	/	/		n:	***
S1317	23029 + 4924	951227	10.3	6.08	5.33	5.19	0.546	/	/	/		n:	***
S1319	23044 + 0200	951226	(10.9)	6.23	5.37	5.36	0.492	/	/	/		n:	***
S1326	23125 + 4921	951227	10.7	5.87	5.07	4.85	0.602	/	/	/		n:	***
S1327	23130 + 5002	951227	10.4	5.87	5.10	4.96	0.588	/	/	/		n:	***
S1330	23172 + 5745	951225	11.1	5.22	4.55	4.42	0.978	0.222	/	/		n	***
S1335	23285 + 4259	970102	9.2	3.81	3.59	3.37	3.881	1.094	/	/			***
S1341	23466 + 2621	970102	11.3	4.10	3.83	3.62	2.200	0.607	/	/		n	***
Sf9	02176 + 6110	971023	11.2[a]	4.58	4.49	4.08	1.398	/	/	/		n:	***
Sf15	04118 + 4851	971023	11.9[a]	4.65	4.86	4.79	0.533	/	/	/		n:	***
Sf57	20255 + 3758	971024	11.4[a]	4.66	4.73	4.65	0.670	/	/	/		n:	***
Sf61	20502 + 4833	971024	11.9[a]	5.36	5.59	5.40	0.839	0.187	/	/			***
Sf68	21336 + 5343	971024	10.2[a]	4.90	4.95	4.69	0.389	/	/	/		n:	***

[a] The I magnitude is listed.

Several points in Tables 2 and 3 are worth noticing. There are 10 stars in our sample having been observed in two seasons and the magnitude differences between two observations are less than 0.1 or 0.2. The only exception is for the Tc-deficient star S87 = BD +24°620 = V1135 Tau, which fainted from Dec. 1995 to March 1996 by $0\overset{m}{.}7$, $0\overset{m}{.}4$ and $0\overset{m}{.}1$ in J, H and K respectively. Although it became reasonably redder while getting fainter, as an AGB star usually does, the variation of $0\overset{m}{.}7$ in J within 80 days merits our attention in the future[1]. Of the Tc-rich and Tc-deficient stars studied here, 12 were observed at JHK bands in Paper I as well. Among them, half varied very little (less than $0\overset{m}{.}1$) compared with the previous data; some others showed somewhat large and reasonable variations ($0\overset{m}{.}2$–$0\overset{m}{.}4$); but the Tc-rich star S49 = HD 14028 = W And apparently brightened by 0.9, 0.8 and 0.7 magnitude in J, H and K, respectively, perhaps which is understandable as it is a well-known Mira variable with a period of 397 days and it has a very large variation range of 6.7–14.6 in V magnitude (Kholopov et al. 1985-87, the *General Catalog of Variable Stars*, hereafter GCVS). Furthermore, it should be noted that there are 116 S stars studied in this paper without JHK data in CIO and 21 other stars with only K data in that catalog, so it appears that we are presenting the first observations in the near infrared for such a large number of S stars.

[1] Dr. A. Jorissen has informed us that given the orbital elements of Jorissen et al. (1998) and an unpublished time of periastron passage T_0 = JD 2448293, the fading was, as it happened, close to the time of passage of the companion behind the giant star (Jorissen 2001). With only one measurement available, it is however impossible to tell whether this strong light change is related or not to the orbital phase.

4. Discussion

4.1. $(K - [12]) - ([12] - [25])$ two-color diagram

In Paper I, a variety of infrared two-color diagrams, including the $(J-H)-(H-K)$, the $([12]-[25])-([25]-[60])$, the $(K-[12])-([12]-[25])$ and the $(J-K)-([12]-[25])$, were presented to test the best way to distinguish those two categories of S stars through their infrared colors. We found from these diagrams that (1) both categories of S stars have almost the same color distribution in the near infrared, so they cannot be segregated by their near infrared colors; and (2) great differences occur in the 2–25 μm bands: the $K - [12]$ and $[12] - [25]$ are the most sensitive colors and the $(K - [12]) - ([12] - [25])$ the most appropriate color-color diagram for segregation of the two kinds of stars.

Merging the data here with those in Paper I, we have near infrared magnitudes together with IRAS fluxes for a total of 35 Tc-rich S stars and 34 Tc-deficient ones, which are almost all of the S stars whose Tc properties are definitely known at present and that can be observed using the 1.26-m IR telescope of the Beijing Astronomical Observatory. Thus a new $(K - [12]) - ([12] - [25])$ diagram with a more comprehensive sample is plotted in Fig. 2 (the IRAS fluxes are transformed into magnitudes without color corrections according to Cheeseman et al. 1989), which shows no fundamental difference with the old one in Paper I. Now the Tc-deficient stars are actually concentrated on the area of $0.3 < K - [12] < 1.0$ and $-0.1 < [12] - [25] < 0.25$, which would be taken as the criteria of a candidate belonging to the Tc-deficient family.

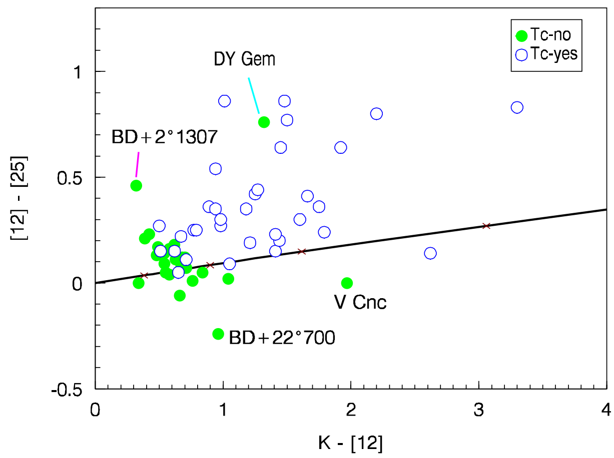

Fig. 2. $(K-[12])-([12]-[25])$ diagram for Tc-rich and Tc-deficient S stars, where the open circles stand for Tc-rich stars and the filled circles for Tc-deficient stars. The solid line represents black body colors, with crosses (from left to right) corresponding to temperatures of 5000, 3000, 2000 and 1250 K respectively.

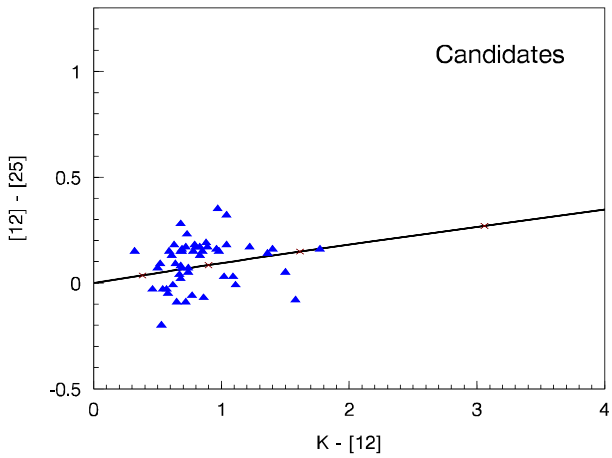

Fig. 3. $(K-[12])-([12]-[25])$ diagram for the observed candidates. Crosses on the black body line indicate the same temperatures as in Fig. 2.

Tc-deficient S stars S96 = BD + 22°700, S231 = DY Gem, S233 = BD + 2°1307 and S494 = V Cnc, and Tc-rich ones S114 = o^1 Ori, S422 = NQ Pup, S1053 = HD 170970 and S1070 = V679 Oph are exceptions to such a partition, as previously noted and explained by Groenewegen (1993), Jorissen et al. (1993), Chen et al. (Paper I) and Jorissen & Knapp (1998). An additional Tc-rich star, S1193 = BD + 4°4354, is located on the boundary of the Tc-deficient region (with $K-[12]=0.67$ and $[12]-[25]=0.22$). A radial-velocity monitoring for it over 3000 days showed no evidence of binarity (Jorissen et al. 1998). We also note that despite being claimed with quality 3 in IRAS PSC, the 25 μm flux of BD + 4°4354 is relatively weak (close to the IRAS detection threshold) and is associated with a relatively large uncertainty of 15%, which we would rather propose to be responsible for the improperly bluer $[12]-[25]$ color. Moreover, it is interesting to note that Tc-deficient Mira star V Cnc varies in V magnitude between 7.5 and 13.9 (GCVS) but, surprisingly, has hardly varied in J, H and K from the measurement of Catchpole et al. (1979) to that of Chen et al. (1988), then to that in Paper I, and then to that given here. Further investigation for V Cnc is needed.

Following the paradigm of Fig. 2, the $(K-[12])-([12]-[25])$ two-color diagram for the candidates is plotted in Fig. 3 by which, from all 51 candidates with good quality 25 μm fluxes, we may extract 39 that should, with high probability, be Tc-deficient according to the infrared criteria mentioned above. The results are presented in Table 3 with a letter “n” in the column labelled “Tc”.

4.2. K − [12] histogram

As mentioned above, only 51 stars, out of the 124 candidates studied here, have good fluxes in 25 μm band (see Table 3). For the remainder, $K-[12]$ is the only infrared color that can be utilized to classify them. Happily, the $K-[12]$ appears a more efficient dividing tool than the $[12]-[25]$: most of the stars distinguishable in the two-color diagram are in fact well discernible even if one uses the $K-[12]$ color alone (as may be seen from Fig. 2).

The histogram of $K-[12]$ color for Tc-rich and Tc-deficient S stars observed here and in Paper I is drawn with a sample size of 0.2 in Fig. 4, which includes more stars than Fig. 2. This histogram makes it immediately obvious that there is a criterion line at $K-[12]=1.0$. Almost all Tc-deficient stars can be found in the left area ($K-[12]<1.0$). The two peculiar objects with $K-[12]$ apparently larger than 1 are S231 = DY Gem and S494 = V Cnc, which have been mentioned in Sect. 4.1. In addition three stars have $K-[12]\sim 1$ (actually, in a range 0.9–1.1). On the other hand, most, though not all, Tc-rich ones are distributed in the right area (with $K-[12]>1.0$). Besides the five Tc-rich stars for which both the $K-[12]$ and $[12]-[25]$ colors look abnormal, as shown in Fig. 2, four others, S803 = S UMa (out of the region populated by Tc-deficient S stars in Fig. 2) and S89 = BD + 23°654, S411 = HD 63733 and S416 = BD − 4°2121 (these three stars are out of but close to the Tc-deficient region in Fig. 2), are also located to the left in Fig. 4. The ambiguity for HD 63733 has been commented on by Jorissen et al. (1993), and a spectroscopic orbit with a period of 1160 d has been derived for it by Udry et al. (1998). The radial-velocity data presented by Udry et al. (1998) also revealed clear velocity variation associated with orbital motion for the Mira star S UMa, but no such variation was seen (also see Jorissen et al. 1998) for BD −4°2121.

From the $K-[12]$ histogram for the candidates presented in Fig. 5 it is seen that an overwhelming majority of the candidates have $K-[12]<1.0$ and thus likely belong to the Tc-deficient category. This conclusion implies that our preliminary selection criteria proposed in Sect. 2 stand to reason. The possible Tc-deficient stars judged only by $K-[12]$ color (due to the absence of a good 25 μm flux) are indicated with “n:” in the “Tc” column of Table 3. We take these stars as very likely Tc-deficient ones not only

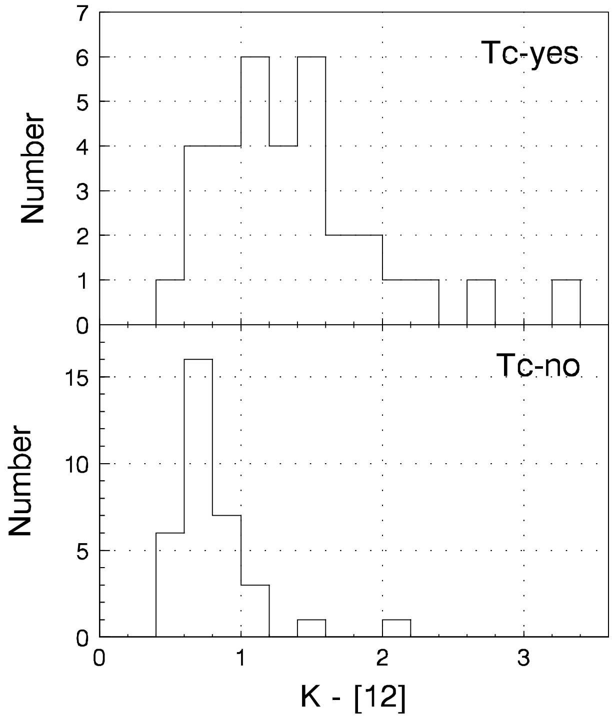

Fig. 4. $K-[12]$ histogram for Tc-rich and Tc-deficient S stars.

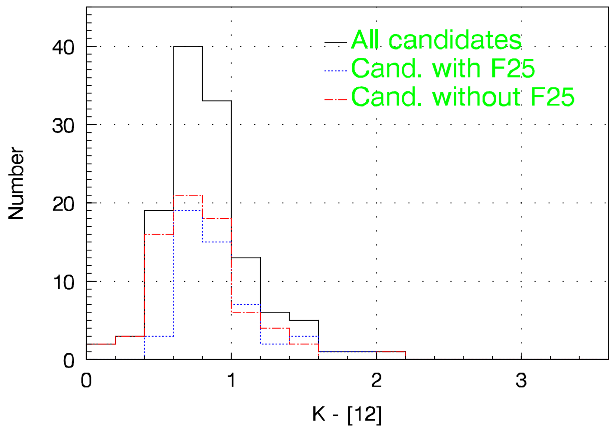

Fig. 5. $K-[12]$ histogram for the observed candidates (solid line). The distributions of the candidates with (dotted histogram) and without (dot-dashed histogram) good quality 25 μm fluxes are also presented.

because the $K-[12]$ color is a relatively reliable rule for the distinction between the two categories as pointed out above, but also because the absence of good 25 μm flux itself implies quite a low flux near or under the IRAS detection threshold, which leads to a relatively small $[12]-[25]$ color that should characterize a Tc-deficient star. Of the 73 candidates without good fluxes in the 25 μm band, 65 are members of the Tc-deficient class (as indicated by the dot-dashed histogram in Fig. 5). The very high frequency ($65/73=89\%$) itself supports the supposition that such candidates frequently show Tc-deficient properties.

Some other stars have $K-[12]<1.0$ but do not fall into the Tc-deficient area of $(K-[12])-([12]-[25])$ diagram due to improper $[12]-[25]$ colors; therefore they should not be looked upon as good candidate Tc-deficient S stars and they are indicated with "n?" in Table 3. Four stars, S1169, S1211, S1219 and S1308, are such cases.

Table 4. Distributions of Tc-rich and Tc-deficient S stars among the LRS classes.

	Sum	E	F	S	I
Tc-no	11	...	2(18%)	8(73%)	1(9%)
Tc-yes	30	9(30%)	8(27%)	11(37%)	2(7%)

4.3. LRS classification and spectral energy distribution

Chen & Kwok (1993) thoroughly studied the IRAS low-resolution spectra of S stars and demonstrated the great importance of the LRS (especially the LRS letter class) to the understanding of the circumstellar properties of this species of chemically peculiar red giants. Jorissen et al. (1993) and Jorissen & Knapp (1998) further discussed the distribution of the various LRS classes in partitioned infrared two-color diagrams. In addition, the different shapes of the LRS spectra of the two kinds of S stars were showed by Groenewegen (1993). A comparison of the LRS letter classification between the two kinds was made by Chen & Kwok (1993) and in Paper I. Now, we await higher-quality ISO data to bring us new information concerning the infrared spectra of S stars. However it seems that the older IRAS LRS material is still of interest because the S stars with ISO observation are very limited in number. A recent inquiry made by us reveals that there are only 22 S stars (among which 11 are Tc-rich, 3 Tc-deficient and 8 Tc-unknown) with ISO SWS and/or LWS spectral data.

What is presented in Table 4 is an extension of the comparisons made by Chen & Kwok (1993) and in Paper I. The present comparison is based on a relatively comprehensive sample reassembled in Table 1. For each of the two categories of S stars the sum of the stars with specific LRS classification is given and the numbers (along with the corresponding percentages) in every LRS group are listed. There is a weak correlation between the Tc content and the LRS class: most Tc-deficient S stars are in LRS group S, which is characterized by photospheric features; all S stars with silicate emission features (in group E) exhibit Tc in their spectra. However, it should be noted that the Tc-rich stars are distributed almost equally among groups E, F and S, and the absolute number of Tc-rich group S stars is even more than that of Tc-deficient group S stars. Only 6 of 124 candidates have an LRS classification and all are in group S. On the other hand, two of them are identified as (quite possible) Tc-deficient members and the others not (see Table 3). This shows again that the LRS classification does not seem so efficient an index for dividing S stars into Tc-rich and Tc-deficient ones unless one can exclude a star of group E without doubt from the Tc-deficient family.

In Paper I we have investigated some Tc-rich and Tc-deficient S stars in the broad band spectral energy distribution (SED) from B (or V) band to 60 μm or to 100 μm band and found that all the SEDs of Tc-deficient stars can be fitted to a single blackbody curve which corresponds to only the photospheric property, whereas many Tc-rich stars (mainly those in LRS group E) demand double blackbody fitting (see Xiong et al. 1994 for the model) which is related to both photospheric and circumstellar properties. This finding is now verified through the SED pattern of 10 more Tc-rich or Tc-deficient sources observed in this paper with good measurements in 60 μm. Moreover, we have 5 candidates in Table 3 which have enough data to fit a SED. None need a double blackbody mode, as 4 stars are noted in LRS group S. Among them, S57, S176 and S212 are possibly Tc-deficient according to the color criteria, but S1211 and S1308 are not (for a somewhat larger [12]−[25]).

5. Summary and remark

Those two categories of S stars lie in different phases of stellar evolution. The contamination of Tc-deficient extrinsic S stars on Tc-rich intrinsic S stars (*real S stars at AGB phase*) has thus considerably affected our knowledge of AGB stars. Therefore it is greatly meaningful to separate the Tc-deficient kind from the Tc-rich one.

In this paper we present near infrared photometry of 161 S stars (for most of them, these are the first observations in the near infrared). The $(K-[12])-([12]-[25])$ two-color diagram and the $K-[12]$ histogram are presented on an extended sample to further investigate the distinguishable properties of the two S star families. Then a larger number of candidates are tested in the infrared property and 104 stars are identified as very likely Tc-deficient S stars. Moreover the IRAS LRS classification and the spectral energy distribution are discussed for those known Tc-rich and Tc-deficient S stars, and for the candidates as well. These infrared-selected Tc-deficient S stars make up a good sample for a deep study of the physical properties and the evolutionary status of this species of S stars.

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