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Newly Identified Silicate Carbon Stars from IRAS Low-Resolution Spectra *

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Abstract The discovery of silicate carbon star poses a challenge to the theory of stellar evolution in the late stage, hence it is important to look for more silicate carbon stars. To this end we have carried out cross-identifications between the new IRAS Low-Resolution Spectrum (LRS) database and the new carbon star catalog, CGCS3. We have found nine new silicate carbon stars with silicate features around 10μm and/or 18 μm. These newly identified stars are located in the Regions IIIa and VII in the IRAS two-color diagram, which means they indeed have typical far infrared colors of silicate carbon stars. The infrared properties of each of these sources are discussed.

Key words: stars: AGB and post-AGB – star: carbon – infrared: stars

1 INTRODUCTION

One of the important discoveries from the IRAS observations is carbon stars with the silicate feature, the so-called silicate carbon stars. This discovery posted a challenge to the classical theory on late stage of stellar evolution. In the theory, the spectral classes of M, S and C stars with the initial mass about 1–8 $M_\odot$ are believed to form an evolutionary sequence for stars on the asymptotic giant branch (AGB) (e.g. Iben et al. 1983; Chen et al. 1993). In detail, these AGB stars begin as oxygen-rich (C/O< 1) stars with spectral type M and in their circumstellar shells they often show features of oxygen-rich material in the infrared such as the amorphous silicate features in emission or in absorption at 10 and/or 18 μm. As a result of carbon dredge-up from the interior they evolve through the stage of spectral type S (C/O$\approx$1) to the so-called carbon stars (C/O> 1). Carbon stars are often characterized by carbon-rich material in their circumstellar shells, such as the amorphous carbon and/or silicon carbide (SiC) at $11.2\,\mu m$ in the infrared. After the IRAS mission, the IRAS low-resolution spectra (LRS) have become an important tool in the infrared for discriminating between oxygen-rich M stars and carbon stars, with the amorphous silicate features at 10 and/or 18μm as indicator of oxygen-rich stars and the silicon carbide (SiC) featured at 11.2μm as indicator of carbon-rich stars (Olnon et al. 1986; Kwok et al. 1997).

However, after cross-identifications between the IRAS sources with the LRS spectra in the IRAS LRS Atlas (Olnon et al. 1986, hereafter LRS Atlas) and the carbon stars from A General Catalogue of Cool Galactic Carbon Stars (Stephenson 1973, hereafter CGCS1, including some earlier literature), Little-Marenin (1986) and Willems et al. (1986) discovered nine carbon stars with the amorphous silicate emission features at 10 and/or 18 μm. Subsequently, many people have done much work either to find more such objects or to find some possible theories/models that will explain their existence. Up to 1999, as Chen et al. (1999) summarized, Chan et al. (1991), Kwok et al. (1993), Chen et al. (1994) and Kwok et al. (1997)

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found 15 new silicate carbon stars from cross-identifications between the IRAS sources with LRS spectra and carbon stars in A General Catalogue of Cool Galactic Carbon Stars, Second edition (Stephenson 1989, hereafter CGCS2). Furthermore, Groenewegen (1994) found another silicate carbon star, IRAS 13198–6224. After removing two misidentified sources, CGCS1 1633 and CGCS1 2123 from Willems's samples (Le Bertre et al. 1990; Lloyd Evans 1990), by the end of 1999 the number of silicate carbon stars discovered had increased to 23 in total. Recently, from the ISO spectral observations the Red Rectangle = HD 44179 = V777 Mon (Waters et al. 1998) and IRAS 09425–6040 (Molster et al. 1999, 2001) have been found to be new silicate carbon stars with the crystalline silicate emission features at wavelengths longer than 15 μm, and IRAS 03201+5459 was found to be the only silicate carbon star with the amorphous silicate feature in absorption at 10 μm (Jiang et al. 2000). Thus, up to now known silicate carbon stars number 26 in total, not including a possible one suggested by Chen et al. (2001). In addition, the detection of OH and H_2O masers toward many silicate carbon stars confirmed that they are indeed associated with oxygen-rich circumstellar material (e.g. Nakada et al 1987, 1988; Benson et al. 1987; Little-Marenin et al. 1988; Barnbaum et al. 1991; Engels 1994; Szymczak et al. 2001).

On the other hand, early on Little-Marenin (1986) proposed a model for the silicate carbon star phenomenon that consists of a carbon-rich giant and an oxygen-rich giant in a binary system. However, this is now thought to be unlikely because no evidence of oxygen-rich giants in silicate carbon stars have been found (Lambert et al. 1990; Engels et al. 1994). Willems et al. (1986) and Chan et al. (1991) suggested that silicate carbon stars are the transition objects between the earlier oxygen-rich stars, and the later carbon-rich stars and, for instance, the oxygen-rich silicate is the remnant of a previous mass-loss from the oxygen-rich star phase. However, this transition model is deemed to be also unlikely because, as Lloyd Evans (1990) pointed out, the time scale for such a transitional object to be observed as a silicate carbon star is predicted to be a few decades, while some of the silicate carbon stars are known to have carbon-rich photospheres for about 50 years already (Little-Marenin et al. 1987a). Furthermore, from the ISO observations, Yamamura et al. (2000) found that the silicate features in the typical silicate carbon star V778 Cyg exhibit no temporal variation for 14 years after the IRAS LRS observation, which makes it unlikely that silicate carbon stars are short-lived transition objects. At present the most widely accepted model is that, instead of an M giant companion, silicate carbon stars have a low-luminosity companion, and oxygen-rich material was shed by mass loss when the primary star was an M giant and this oxygen-rich material is stored in a circumbinary disk (Morris 1987; Lloyd Evans 1990) or in a circumstellar disk around the companion (Yamamura et al. 2000) until the primary star becomes a carbon star. In fact, there is some evidence for the binary nature and the presence of such a disk in some silicate carbon stars. Radial velocity measurements of two silicate carbon stars, BM Gem and EU And, made by Barnbaum et al. (1991) are consistent with motion in a binary system. The presence of long-lived reservoirs of orbiting gas was inferred from the CO emission lines for BM Gem and EU And obtained by Kahane et al. (1998) and Jura et al. (1999). The presence of a low-luminosity companion surrounded by an accretion disk was found in the violet spectrum of BM Gem (Izumiura 2003). In addition, the recent high-resolution H_2O maser maps toward V778 Cyg by Szczerba et al. (2006) suggest the existence of a rotating disk, and the high-resolution spectro-interferometric observations and the radiative transfer calculations of a silicate carbon star (Hen 38 = IRAS 08002–3803) by Ohnaka et al. (2006) lend support to the picture where oxygen-rich material around Hen 38 is stored in a circum-binary disk surrounding the carbon-rich primary star and its putative low-luminosity companion. All those observations confirmed the binary model consisting of a carbon star and a low-luminosity companion for silicate carbon stars.

As mentioned above, silicate carbon stars known so far are found mainly from cross-identifications between the CGCS1/CGCS2 catalogues and the IRAS LRS Atlas. It should be emphasized that the CGCS1 catalogue contains only 3219 carbon stars mainly based on spectral observations in the optical, and the CGCS2 catalogue contains 5987 carbon stars by adding optically discovered carbon stars in the years 1973 to 1989 and also 176 new infrared carbon stars noted by Little-Marenin et al. (1987b) based on the presence of the SiC emission feature at 11.2 μm in their IRAS LRS spectra. Recently Alksnis et al. (2001) published the third edition of the galactic carbon star catalog: General Catalog of Galactic Carbon Stars by C.B. Stephenson (hereafter CGCS3). In this catalog new carbon stars discovered with the optical method and the IRAS LRS method from 1989 to 2000 are included and many sources identified with the infrared two color method proposed by Epchtein et al. (1987) and Fouque et al. (1992) are also added. Thus in this catalog the number of carbon stars totals 6891, about one thousand more than in the GCGS2 catalog. On the other hand, in the IRAS LRS Atlas the LRS spectra only total 5425. In 1997 Kwok et al. (1997) doubled this number to 11224. It is strongly expected that, considering the greatly increased numbers of carbon stars and LRS spectra, a cross-identification between the CGCS3 catalog and the new LRS database presented by Kwok et al. (1997, hereafter new LRS database) will result in new identifications of silicate carbon stars. Such a cross-identification is made in this paper and some properties in the far infrared of the new finds will be discussed.

2 WORKING SAMPLE AND DATA PROCESSING

In the CGCS3 catalog the carbon stars numbered from 6000 to 6924 are newly identified carbon stars that were not listed in the CGCS1 and CGCS2 catalogs. On the other hand, Kwok et al. (1997) sorted out raw database of IRAS LRS spectra using the letter classification scheme proposed by Volk et al. (1989) and published an expanded LRS database in which the number of sources totals 11224, which is more than twice the number in the LRS Atlas. In the new LRS database the sources are sorted into 10 classes according to their spectral characteristics, in which the class E is considered to have the 10 μm amorphous silicate emission feature. It should be emphasized that if a carbon star is found to have an LRS spectrum of Group E, then it certainly is a silicate carbon star according to the definition proposed by Little-Marenin (1986) and Willems et al. (1986). Therefore the CGCS3 catalog and the new LRS database are taken to be our basic working sample. Besides new carbon stars in the CGCS3 catalog, the old ones numbered from 1 to 5999 were also re-examined for silicate carbon stars that were possible missed before.

First of all, the coordinates in the CGCS3 catalog and the coordinates in the IRAS Point Source Catalog (1989, hereafter IRAS PSC) are compared to find possible associations. It should be noted that in the CGCS3 catalog the sources come from different observations with very different observational accuracies, i.e., the CGCS3 catalog is not homogeneous in the source positions, which usually have an accuracy of about 10–30 arc-second. In order to overcome the positional inhomogeneity in the CGCS3 catalog, the USNO-B1.0 catalog (Monet et al. 2003, hereafter USNO) and the 2MASS Point Source Catalog (2MASS Home Page 2003, hereafter 2MASS) were used to obtain relatively good positions for the relevant CGCS3 sources. The USNO catalog contains over one billion sources with average positional accuracy better than one arc-second and with magnitudes in B/R bands down to about 22–23 (Monet et al. 2003) while the 2MASS catalog contains a half billion sources with maximum positional accuracy better than 7 arc-second, covering over 99.9% sky with JHK magnitudes down to about 15–16 (2MASS Home Page 2003). In practice, we made our selections with reference to the recorded positional accuracy in the CGCS3 catalog. If a source from the USNO catalog and/or the 2MASS catalog is located within the error circle of the related carbon star position in the CGCS3, then it can be regarded as a candidate for the carbon star counterpart. If there is only one USNO source and/or only one 2MASS source in the error circle of the carbon star concerned, their association is certain, and if there are more than one USNO sources or 2MASS sources, additional considerations should be made. One such consideration is the magnitude listed in those catalogs, and another important one is the B and R magnitudes given in the USNO catalog and the JHK magnitudes given in the 2MASS catalog after Bessell et al. (1988) and Bessell (1990). Thus in most cases the association of the objects given in those two catalogs and the CGCS3 catalog could be determined. Then we can use the much more accurate coordinates in the USNO catalog and/or the 2MASS catalog to look for their IRAS counterparts. Secondly, the IRAS PSC is used to combine with those given coordinates of carbon stars from the USNO/2MASS catalogs.

Because the positional error ellipse of the IRAS PSC has 95% confidence (1988, IRAS Explanatory Supplement, hereafter IRAS ES), to keep certain confidence and avoid possible mismatch, this positional error ellipse is used as the criterion to identify the IRAS counterpart of the related carbon star, i.e. if the USNO/2MASS position of a carbon star is located in the IRAS source error ellipse, their association is certain. Thus for about 1000 new carbon stars listed in the CGCS3 catalog, 469 IRAS associations are found. Third, the new LRS database (Kwok et al. 1997) is used to find new carbon stars that have the LRS spectra. The number of such is 243, of which 15 have LRS spectra of Group E. Of these 15, nine are of strong confidence and are listed in Table 1. For the other six, more than one USNO/2MASS sources with compatible magnitudes are found within the IRAS error ellipse.

Table 1 New Silicate Carbon Stars

	IRAS (1)	CGCS (2)	LRS (3)	RA(IRAS 2000) (4)	Dec (5)	$r_1('')$ (6)	RA(CGCS3 2000) (7)	Dec (8)	$r_2('')$ (9)
S1	06194+1635	6139	E	062221.2	+163425	0	062221.2	+163425	4.5
S2	09411–5933	6337	E(14)	094236.4	–594740	1.1	094236.3	–594739	5.6
S3	11311–6355	6450	E	113324.8	–641156	0	113324.8	–641156	/
S4	12569–6105	6503	E	130004.1	–612119	0	130004.1	–612119	2.2
S5	14286–4706	6559	E(25)	143157.7	–471944	0	143157.7	–471944	2.6
S6	16001–4851	6612	E(42)	160347.8	–485915	0	160347.8	–485915	
S7	16103–4929	6624	E(44)	161405.5	–493659	1.5	161405.4	–493659	0.9
S8	16328–4656	6650	E(22)	163629.2	–470300	5.9	163628.8	–470300	6.9
S9	18575–0139	4152	E(13)	190008.9	–013456	10.6	190009.6	–013457	0.7

	RA (USNO-B 2000) (10)	Dec (11)	$r_3('')$ (12)	RA (2MASS 2000) (13)	Dec (14)	F12 (15)	F25 (16)	F_{60} (17)	VH (18)	Note (19)
S1	062221.52	+163425.1	2.2	062221.33	+163424.0	8.582	3.708	0.957	II	self-absorption
S2	094236.07	–594733.7	2.3	094236.11	–594737.7	36.09	23.47	4.204	IIIa	
S3	/	/	3.4	113324.62	–641159.2	10.97	7.005	2.193	VII	self-absorption
S4	130004.37	–612120.0	2.2	130004.36	–612120.1	37.21	24.92	4.942	VII	
S5	143157.52	–471943.5	3.6	143157.45	–471943.7	32.81	24.37	3.442	IIIa	
S6	/	/	2.1	160347.94	–485916.0	18.01	25.96	6.606	IIIb	self-absorption
S7	161405.42	–493658.2	1.1	161405.43	–493658.1	21.81	11.56	/	VII	
S8	163628.68	–470306.8	2.4	163628.95	–470258.3	69.16	32.03	12.50	VII	self-absorption
S9	190009.61	–013456.6	0.7	190009.61	–013456.6	16.14	5.609	1.715	VII	

The successive columns of Table 1 are: (1) IRAS name; (2) CGCS3 number; (3) IRAS LRS classification from Kwok et al. (1997) and the LRS Atlas, if any; (4) and (5) Position from the IRAS PSC in the epoch of 2000; (6) The source distance between the IRAS PSC and the CGCS3 in arc-second, note that if the distance is zero the position in the CGCS3 is directly taken from the IRAS PSC; (7) and (8) Position from the CGCS3 at epoch 2000; (9) The source distance between the USNO and the CGCS3 in arc-seconds; (10) and (11) Position from the USNO in the epoch of 2000; (12) The source distance between the 2MASS and the CGCS3 at epoch 2000; (13) and (14) Position from the 2MASS at epoch 2000; (15) to (17) IRAS flux densities in 12, 25 and 60 μm respectively from the IRAS PSC; (18) The region in the IRAS two-color diagram defined by van der Veen et al. (1988, hereafter VH, see below in Section 3); (19) Notes. Furthermore, the IRAS LRS spectra of newly identified silicate carbon stars listed in Table 1 are plotted in Fig. 1 from Kwok et al. (1997).

3 DISCUSSION

As van der Veen et al. (1988) and Omont et al. (1993) pointed out, the IRAS [12]–[25] versus [25]–[60] color-color diagram could be an efficient and simple tool for the classification of AGB and post-AGB stars. This diagram comprises 10 regions, each occupied by a certain kind of objects with distinct infrared colors. Chen et al. (1998) investigated the infrared properties of 17 silicate carbon stars known before 1994. The result in their figure 2 and the result from Chen et al. (2002) in their figure 1 showed that there are clear differences in the distributions of visual (optical) carbon stars, infrared carbon stars and silicate carbon stars: the optical carbon stars are distributed mainly in Region VIa and the left half of Region VII, and the infrared carbon stars, mainly in the right half of Region VII. Of the silicate carbon stars, most are located in Region IIIa and some in Region VII. From the IRAS flux densities shown in Table 1 we can obtain the VH region the source belongs to, whose Roman numeral is given in the column VH.

We see that most of our objects are indeed located in Regions IIIa and VII, which means they indeed have typical far infrared colors of silicate carbon stars.

On the other hand, there are nine objects in Table 1 that are newly identified silicate carbon stars from their IRAS LRS spectra in Figure 1. For a source in Table 1 to be classified as silicate carbon star, it must satisfy the following criteria: the star should be a real carbon star, the silicate features should be found in the infrared spectrum and the association between the carbon star and the IRAS source should be unique. Notes on the individual sources in Table 1 now follow.

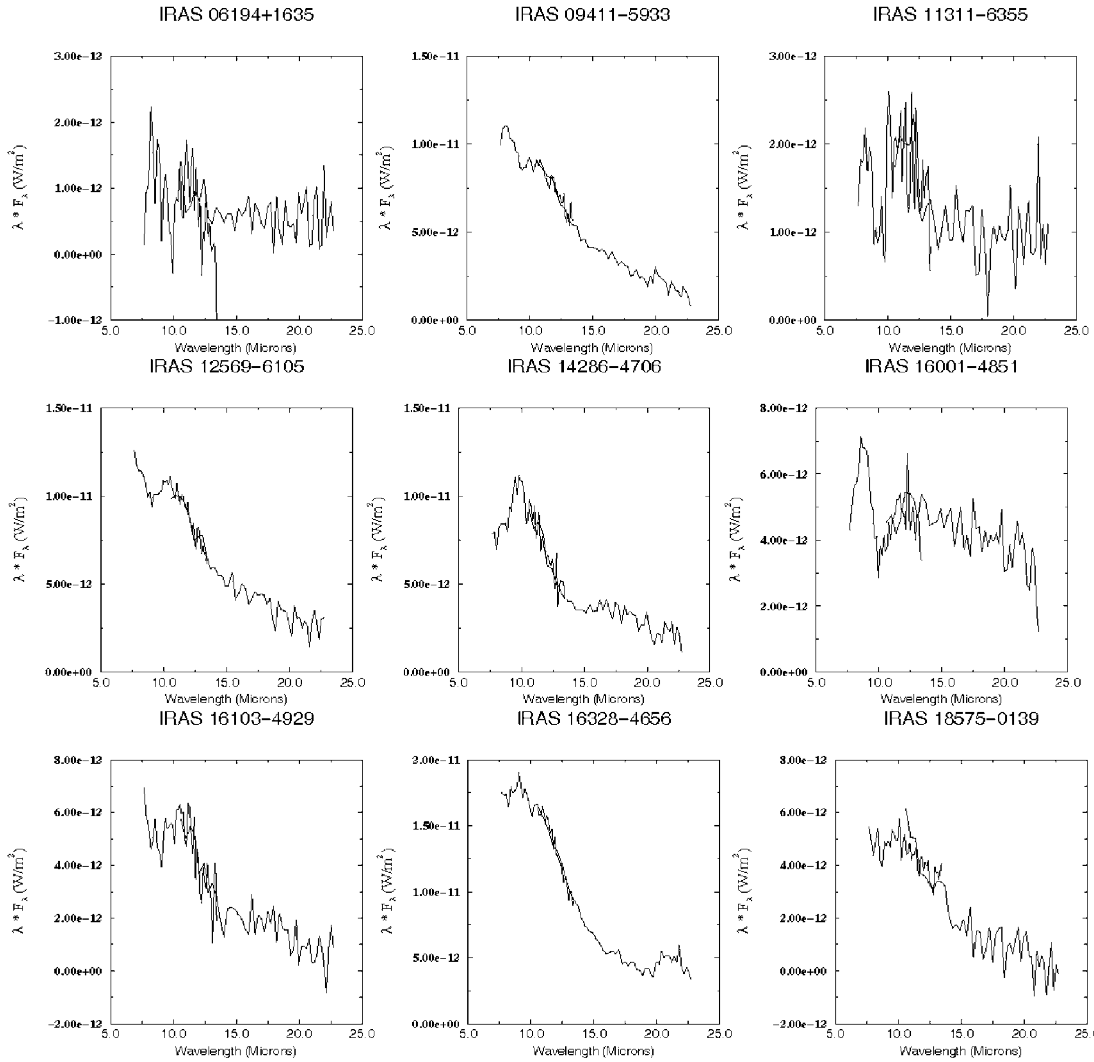

Fig. 1 IRAS LRS spectra for the newly identified silicate carbon stars.

IRAS 06194+1635 = CGCS3 6139: It is seen from Figure 1 that there is a broad emission feature with self-absorption around 10 μm. Kwok et al. (1997) placed it in Group E and noted the self-absorption. Guglielmo et al. (1993) first classified it as a carbon star. There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 09411–5933 = CGCS3 6337: An emission feature around 10 μm is clearly seen in Figure 1. Fouque et al. (1992) first identified it as a carbon star using the near infrared two-color method. Later, it was included in the CGCS3. Gupta et al. (2004) sorted its LRS spectrum to their Group 12 that indicates the weak silicate emission feature. No OH maser emission in 1612 MHz was found in the 1612 MHz OH maser survey (te Lintel Hekkert 1991). There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 11311–6355 = GCGS3 6450: Although its LRS classification is E, it shows clear self-absorption in Figure 1. Kwok et al. (1997) also pointed out this self-absorption. Guglielmo et al. (1993) first identified it as a carbon star using the near infrared two-color method. There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 12569–6105 = CGCS3 6503: An emission feature around 10 μm is clearly seen in Figure 1. Epchtein et al. (1990) first identified it as a carbon star using the near infrared two-color method. Groenewegen et al. (2002) treated it as an infrared carbon star in the millimeter observation. No OH maser emission in 1612 MHz could be found (te Lintel Hekkert 1991). Besides the USNO source with I band magnitude 12.17 listed in Table 1, there are four other USNO sources within the IRAS positional error ellipse, which, however, all have I magnitudes fainter than 15.5, and their contributions would be negligible compared to the listed source. Notably, there is only one 2MASS source listed in Table 1 within the IRAS positional error ellipse.

IRAS 14286–4706 = CGCS3 6559: Figure 1 shows clearly a strong emission feature around 10 μm. Fouque et al. (1992) first identified it as a carbon star using the near infrared two-color method. There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 16001–4851 = CGCS3 6612: Although its LRS spectrum in Figure 1 shows the emission feature with central self-absorption around 10 μm, it was sorted into Group E by Kwok et al. (1997). Epchtein et al. (1990) first identified it as a carbon star. No OH maser emission in 1612 MHz could be found (te Lintel Hekkert 1991). There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 16103–4929 = CGCS3 6624: Its LRS spectrum in Figure 1, though noisy, shows weak emission feature around 10 μm. It is sorted into Group E by Kwok et al. (1997). Epchtein et al. (1987, 1990) classified it as carbon star. There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

IRAS 16328–4656 = CGCS3 6650: An emission feature around 10 μm is seen in Figure 1. Gupta et al. (2004) sorted its LRS spectrum into Group 12 of their classification that indicates weak silicate emission feature. Epchtein et al. (1987) first identified it as a carbon star. There is only one USNO source listed in Table 1 within the IRAS positional error ellipse. It should be pointed out that besides the 2MASS source of K magnitude 2.98, there are two further 2MASS sources within the IRAS positional error ellipse, but their K magnitudes are all greater than 8 so that their contributions in the infrared can be neglected compared with the source listed.

IRAS 18575–0139 = CGCS3 4152: Its LRS spectrum in Figure 1, though noisy, still shows weak emission feature around 10 μm, and Kwok et al. (1997) classified it in Group E. Claussen et al. (1987) first treated it as a galactic carbon star. Then Bothum et al. (1991) listed it as one of the high galactic latitude carbon stars. Abia et al. (1993) and Boffin et al. (1993) identified it as a carbon star with strong Lithium. Abia et al. (1997) again treated it as a carbon star with strong Lithium and gave its spectral type as SC5,8e, and Bergreat et al. (2001) considered it as a carbon-rich giant. Alksnis et al. (2001) and Ducati et al. (2002) gave a spectral type of C9,1p. Recently Zijlstra et al. (2004) claimed it as a SC/CS star with an increasing period. There is only one USNO/2MASS counterpart listed in Table 1 within the IRAS positional error ellipse.

From the discussion above it is concluded that all the sources listed in Table 1 are indeed silicate carbon stars.

4 SUMMARY

In this paper cross-identification between the new IRAS LRS database and the CGCS3 catalog was made in a search for new silicate carbon stars. It is shown that nine new silicate carbon stars have been found here, thus increasing the number of silicate carbon stars in our Galaxy found so far to 35.

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