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Spectral variations of carbon stars based on ISO SWS data *

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Abstract We investigate the spectral variations of seven carbon stars in the infrared using ISO SWS spectral data. Continuum variations of those carbon stars show that during the central star pulsations when carbon stars become fainter in the infrared, their ISO SWS spectra become redder and the near-IR temperature ($T_{\rm nir}$) decreases. When carbon stars become brighter in the infrared, their ISO SWS spectra become bluer and $T_{\rm nir}$ increases. Furthermore, it is found that the shorter the wavelength of spectral features, such as the 2.48+2.58 (C_2H_2+HCN+CO+C_2), 3.05 (C_2H_2+HCN) and 3.90 (C_2H_2) μm features, is, the better the correlation of their relative integrated fluxes with the fluxes of the continuum is. The changes of the 5.2 (C_3), 11.30 (SiC) and 13.70 (C_2H_2) μm features do not obviously correlate with the fluxes of the continuum.

Key words: stars: AGB and post-AGB — stars: mass loss — infrared: stars

1 INTRODUCTION

All stars with initial mass $1.5-2$ to $5-6\,M_\odot$ on the main sequence could evolve through two red-giant phases in their late stages of stellar evolution (e.g., Iben & Renzini 1983; Straniero et al. 1995, 1997). The second red-giant phase is referred to as the Asymptotic Giant Branch (AGB) phase, on which stars usually evolve along the sequence of M→MS→S→SC→C with the C/O ratio in the photosphere increasing from C/O<1 to >1. In the atmospheres of carbon stars where the photosphere of C/O>1, oxygen atoms are tied up in the CO molecules and the rest of the carbon atoms often form carbides, such as C_2, CN, CH, C_3, HCN, C_2H_2, and SiC. These molecules show absorption or emission features in the spectra and are seen as the important characteristics that distinguish the carbon stars from the other AGB stars.

During the AGB phase, pulsations and mass loss of carbon stars cause the dust, such as amorphous carbon grains and SiC grains, to form in the envelopes around these stars. The amorphous carbon dust merely contributes to the dust continuum emission. The SiC dust does exhibit a strong emission feature around 11.30 μm and SiC is believed to be a significant constituent of dust around carbon stars. Many authors (Baron et al. 1987; Goebel et al. 1995; Sloan et al. 1998; Speck et al. 2005) have extensively discussed the effect of the evolution of the density of the dust envelope on the 11.3 μm feature. In general, following the increase of the mass-loss rate, the dust envelope becomes optically thicker and at first the 11.3 μm SiC feature is strong, narrow and sharp, and then broadens, flattens and weakens, and finally appears in absorption when the envelope is extremely optically thick. The evolution of the

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11.3 μm SiC feature is believed to be correlated not only with the optical depth of the envelope but also with the change in the nature of the SiC grains, such as their size distribution (Speck et al. 2005).

On the other hand, most AGB stars, including carbon stars, are intrinsically variable, and they can be divided into different variable types according to the amplitude and the regularity of their visual light curves. The basic variable categories are as follows: Miras, which have regular pulsations with large amplitude ($V \geq$2.5 mag) and periods longer than 60 d; semi-regulars (SRs), which have smaller amplitudes ($V \leq$2.5 mag); and irregulars (Ls) (e.g., Iben & Renzini 1983; Thompson et al. 2006). The investigation of variations for Mira carbon stars is very important because it can not only reveal some physical properties of those carbon stars, but also determine their pulsation periods, and then the period-luminosity relations, which can be used to derive their absolute magnitudes and distances.

The photometric variations of carbon stars in the optical have been studied intensively. The spectroscopic changes of carbon stars in the optical were also reported (e.g., Lloyd Evans 1997). However, carbon stars in the AGB phase usually have effective temperatures of 2500 – 3500 K so that their radiations are mainly in the infrared region. Therefore, investigation of their variations in the infrared is the most important for the understanding of their nature. Photometric variations of carbon stars in the near infrared have been studied by many authors (Whitelock et al. 2000; Kerschbaum et al. 2001; Whitelock et al. 2006).

However, infrared spectroscopic variations of carbon stars have not been extensively studied so far, especially in the mid infrared region, because of the lack of long-term observations. It is noted that ISO SWS has observed some carbon stars many times during one and a half year observations, which enables us to make spectral investigations of variations of those carbon stars in the $2-45\,\mu$m wavelength range. Chen et al. (2009) investigated the infrared spectral variations of three Mira variable carbon stars with the strong 11.30 μm SiC feature, IRAS 15477+3943 = V CrB, IRAS 17556+5813 = T Dra and IRAS 20396+4757 = V Cyg, based on the ISO SWS data.

In this paper, we revisit the carbon stars observed by ISO SWS more than once, such as IRAS 01246 – 3248, IRAS 15477+3943, IRAS 17556+5813, IRAS 20396+4757, IRAS 21168 – 4514, IRAS 21358+7823, and IRAS 23438+0312.

2 DATA COLLECTION AND PROCCESSING

The identification methods of carbon stars are different according to their different evolutionary stages. Visual carbon stars are often identified on the basis of the Swan system of C_2 bands in the optical region and a series of bands of CN and C_2 in the near infrared region. The identification of infrared carbon stars is mainly based on the existence of the 11.30 μm SiC feature. Infrared carbon stars are also identified on the basis of the 3.05 μm absorption due to HCN and C_2H_2. Stephenson et al. (1989) listed 5987 cool carbon stars, showing bands of the Swan system of the C_2 molecule or the red or infrared bands of CN; this catalog was updated and revised by Alksnis et al. (2001). Carbon stars with the 11.30 μm SiC feature are mainly identified from the IRAS Low-Resolution Spectra (LRS). Little-Marenin et al. (1987), Chan & Kwok (1990), Jura & Kleinmann (1990) and Chen & Chen (2003) identified about 260 carbon stars on the basis of the 11.30 μm SiC feature from the IRAS LRS (these carbon stars are called infrared carbon stars).

Many carbon stars were observed with the ISO Short Wavelength Spectrometer (SWS), and among them seven carbon stars were observed more than once; the ISO Data Archive provides their spectral data with high quality. From Kraemer et al. (2002) and Sloan et al. (2003), the Highly Processed Data Products (HPDP) of ISO SWS spectra for those seven carbon stars can be obtained and are plotted in Figure 1. It can clearly be seen that, for those carbon stars, the main molecular bands are the C_2H_2+CO absorption at 2.48 μm, the HCN+C_2 absorption at 2.58 μm, the HCN+C_2H_2 absorption at 3.05 μm, the C_2H_2 absorption at 3.90 μm, the C_3 absorption at 5.20 μm, the C_2H_2 absorption at 13.70 μm appearing in most of studied samples, and the main dust features at 11.30 μm which appear in all of the studied samples except IRAS 23438+0312 (e.g., Yang et al. 2004).

Among the seven stars, four carbon stars have 6–8 spectra and the other three merely have two spectra. We will focus on the four carbon stars observed many times. The necessary information, including

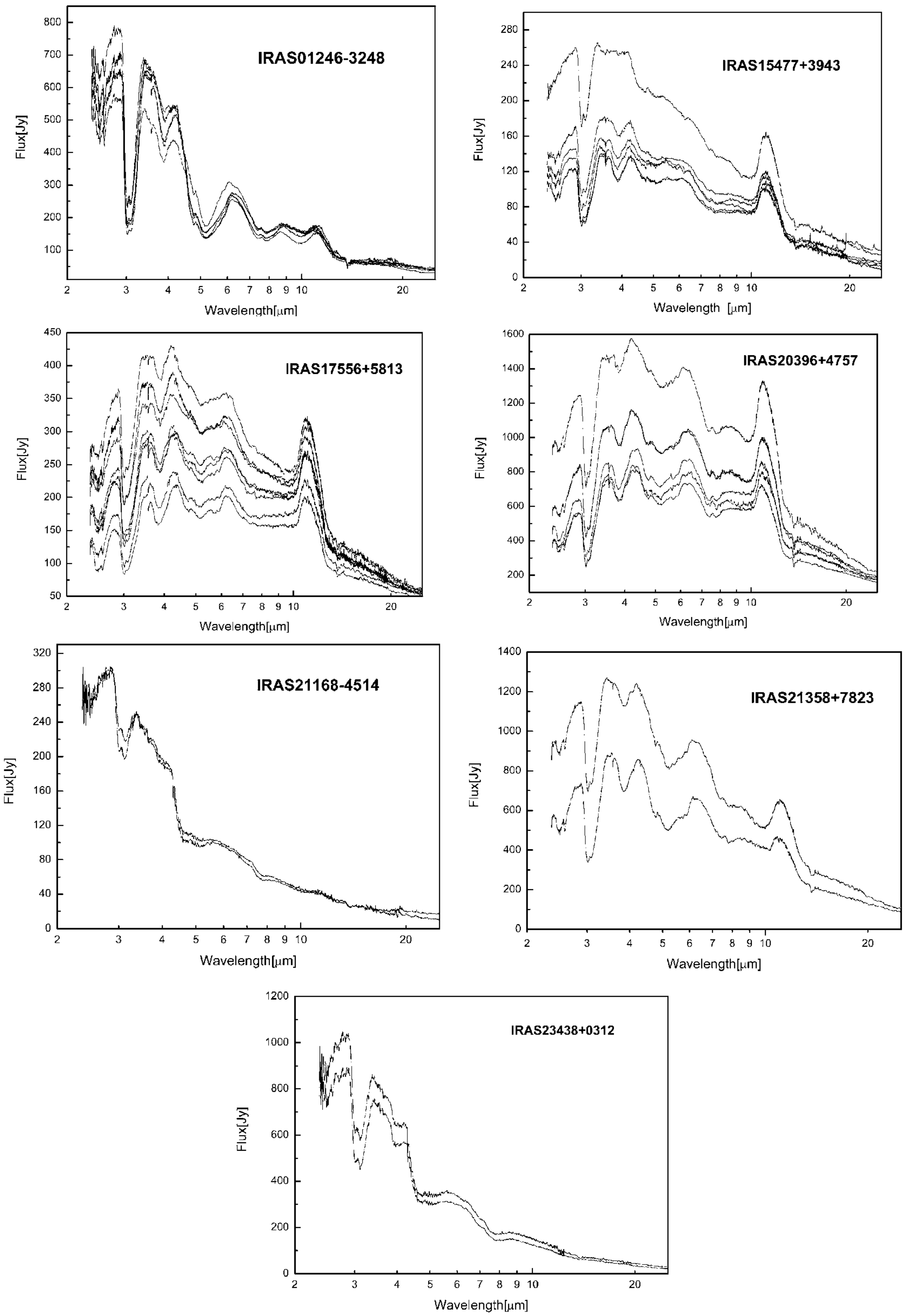

Fig. 1 ISO SWS spectra of seven carbon stars.

Table 1 Spectral Data of Seven Carbon Stars

IRAS Name	Name	ISO TDT	Obs. date	$\bar{F}_{2.77}$ [Jy]	$\bar{F}_{3.48}$ [Jy]	$\bar{F}_{4.175}$ [Jy]	$F_{2.48+2.58}$	$F_{3.05}$	$F_{3.90}$	$F_{5.20}$	$F_{11.30}$	$F_{13.7}$
01246–3248	R Scl	24701012	1996–07–21	768.3	657.2	541.9	0.083	0.291	0.047	0.273	0.159	0.099
		37801213	1996–11–28	670.3	665.3	541.0	0.093	0.301	0.071	0.336	0.104	0.098
		37801443	1996–11–28	677.2	674.3	545.1	0.089	0.301	0.076	0.337	0.116	0.094
		39901911	1996–12–19	623.7	631.8	511.6	0.110	0.343	0.104	0.352	0.096	0.088
		41401514	1997–01–03	633.1	639.0	515.7	0.116	0.352	0.114	0.350	0.105	0.082
		56900155	1997–06–07	561.2	511.8	436.9	0.119	0.329	0.084	0.282	0.163	0.090
15477+3943	V CrB	11105149	1996–03–07	133.6	145.9	146.2	0.069	0.247	0.069	0.038	0.253	0.048
		42200213	1997–01–11	119.8	137.6	132.4	0.098	0.264	0.094	0.071	0.259	0.079
		42300201	1997–01–12	119.8	139.6	133.7	0.103	0.256	0.096	0.072	0.228	0.045
		47600302	1997–03–06	143.2	156.5	154.6	0.058	0.221	0.064	0.050	0.245	0.082
		57401003	1997–06–12	252.3	258.2	255.1	/	0.130	0.004	0.043	0.237	0.062
		67600104	1997–09–21	160.9	179.7	175.0	0.042	0.205	0.048	0.075	0.237	0.045
17556+5813	T Dra	11101727	1996–03–07	167.2	226.0	232.2	0.126	0.238	0.101	0.089	0.219	0.032
		24800101	1996–07–21	277.2	340.7	355.3	0.072	0.169	0.049	0.046	0.230	0.039
		34601702	1996–10–28	342.2	414.4	428.6	0.063	0.177	0.046	0.067	0.232	0.020
		38303014	1996–12–04	299.6	372.1	383.4	0.083	0.198	0.060	0.081	0.246	0.023
		42902712	1997–01–18	230.7	297.7	303.0	0.103	0.229	0.166	0.093	0.227	0.021
		43700103	1997–01–26	218.5	285.3	290.6	0.111	0.235	0.088	0.092	0.255	0.023
		54600104	1997–05–15	145.0	201.0	206.2	0.139	0.200	0.081	0.055	0.231	0.033
		64500205	1997–08–21	215.2	278.5	289.0	0.144	0.202	0.080	0.055	0.232	0.029
20396+4757	V Cyg	08001855	1996–02–05	527.5	740.8	792.1	0.114	0.248	0.104	0.095	0.238	0.042
		42100111	1997–01–10	778.8	1055.0	1146.9	0.080	0.216	0.067	0.087	0.226	0.036
		42300307	1997–01–12	773.5	1054.8	1153.5	0.086	0.212	0.071	0.089	0.215	0.041
		51401308	1997–04–13	534.2	768.5	818.2	0.132	0.254	0.109	0.111	0.228	0.042
		59501909	1997–07–03	608.8	843.2	901.5	0.133	0.246	0.102	0.099	0.228	0.040
		69500110	1997–10–10	1194.5	1467.6	1571.7	0.059	0.182	0.034	0.061	0.217	0.037
21168–4514	T Ind	37300427	1996–11–23	299.3	241.0	191.8	0.057	0.098	0.021	0.201	0.026	/
		71800602	1997–11–02	295.5	237.6	187.3	0.053	0.131	0.032	0.219	0.046	/
21358+7823	S Cep	56200926	1997–05–31	1115.0	1261.5	1234.2	0.053	0.173	0.047	0.115	0.153	0.048
		75100424	1997–12–05	699.3	878.4	843.4	0.108	0.261	0.099	0.294	0.119	0.050
23438+0312	TX Psc	55501379	1997–05–24	1016.5	830.2	648.0	0.062	0.183	0.038	0.222	/	/
		75700419	1997–12–11	865.2	740.4	569.9	0.069	0.218	0.042	0.214	/	/

Cols. (1), (2), (3), and (4) are IRAS name, common name, ISO TDT number, and observation date, respectively; Cols. (5), (6), and (7) the average fluxes of the 2.77, 3.48, and 4.175 μm bands, respectively; Cols. (8)–(13) the relative integrated fluxes of the 2.48+2.58, 3.05, 3.90, 5.20, 11.30, and 13.70 μm absorption features, respectively. The slashes in the table mean that the features do not exist in the ISO spectra.

ISO TDT numbers and the observing time (the UT) from the ISO Data Archive, are listed in Table 1. The other information listed in Table 1 will be described in the following section.

3 DATA ANALYSIS AND DISCUSSION

3.1 The Variation Properties of Continua

Figure 1 clearly shows that during ISO SWS observations the infrared spectra of the seven studied carbon stars were indeed variable with time. The continuum fluxes of IRAS 15477+3943, IRAS 17556+5813, IRAS 20396+4757 and IRAS 21358+7823 obviously vary in the wavelength region shorter than about 20 μm, and the continuum fluxes of the others show weaker variation in the wavelength region longer than about 10 μm. It is noted that according to the classification system by Yang et al. (2004), who have examined the ISO SWS spectra of 29 carbon stars, IRAS 15477+3943, IRAS 17556+5813, IRAS 20396+4757 and IRAS 21358+7823 should belong to Group B and the other three stars should belong to Group A. In Yang et al.'s classification system (Yang et al. 2004), stars become increasingly red from Group A to D and the circumstellar envelopes become thicker. On account of the observation interval time not being beyond one and a half pulsation periods, Figure 1 indicates that the circumstellar envelopes of the four stars in Group B can be influenced by the central star pulsations, while the pulsation influence becomes weaker for the outer-circumstellar envelopes.

In order to show the properties of spectral variation, we collect the information about the fluxes of three bands defined in this paper and the relative integrated fluxes of spectral features in Table 1. Here, to trace the change of the continua, we define a set of narrow bands centered at 2.77, 3.48 and 4.175 μm, respectively. Table 1 lists the average fluxes of the three bands with the wavelength region of 2.67 – 2.87, 3.40 – 3.56 and 4.10 – 4.25 μm. The correction of interstellar extinction is made using the van Herk relation (van Herk 1965) and the reddening law from Schlegel (1998). The relative integrated flux of 2.48+2.58, 3.05, 3.90, 5.20, 11.30 and 13.70 μm features are also calculated. The relative integrated flux is defined as the ratio of the quantity derived by the subtraction of the integrated continuum flux. Although the line widths of the different objects for the same line feature are different, we integrate over the same fixed wavelength range for each line feature to derive its integrated flux. The integration ranges are: 2.40 – 2.76 μm for the 2.48+2.58 μm feature due to the partial overlapping of the 2.48 and 2.58 μm features; 2.85 – 3.50 μm for the 3.05 μm feature; 3.60 – 4.20 μm for the 3.90 μm feature; $4.10-6.50$ μm for the 5.20 μm feature; $9.00-13.60$ μm for the 11.30 μm feature and $13.40-14.30$ μm for the 13.70 μm feature. The wavelength range of $4.10 - 6.50$ μm also includes the strong CO fundamental band.

The 2.77 μm band flux is used to trace the change of spectra. To show how this band flux varies with time during the ISO SWS observation, we plot Figure 2, where the x-axis is the observation interval relative to the first spectrum divided by the period. From Figure 2, among the four carbon stars with more than two observations, the 2.77 μm band average flux of IRAS 17556+5813 seems to show a more obvious periodical variation than the others due to them having a non-uniform observation interval time. IRAS 21168 – 4514, IRAS 21358+7823 and IRAS 23438+0312 have only two spectra. Though the observation interval time of IRAS 21168 – 4514 is twenty-one days, from Figure 1, we can see the obvious change of the 3.05 and 5.20 μm features, but the change of continuum is negligible. IRAS 21358+7823 and IRAS 23438+0312 show obvious variations in either continuum or spectral features within the large time span that is not beyond one period.

Figure 3 plots a color-color diagram of ([2.77]–[4.175])$-$([2.77]–[3.48]) and a relationship of [2.77]–[4.175] with the average flux of the 2.77 μm band. Here, the fluxes corresponding to zero magnitude in different bands are not considered, because all the observations were made with ISO SWS and the correction of zero-magnitude fluxes to colors are constant for those studied samples, so that the relationship between the [2.77]–[4.175] color and the [2.77]–[3.48] color does not change intrinsically. From Figure 3, it is seen that all the data points lie around the blackbody line, which indicates that those two colors [2.77]–[3.48] and [2.77]–[4.175] can be used as indicators of T $_{\rm nir}$. The colors [2.77]–[3.48] and [2.77]–[4.175] increase with the decrease of $T_{\rm nir}$. A plot of the [2.77]–[4.175] color against the average flux of the 2.77 μm band in Figure 3 shows the change of the color during the central star pulsations. From this figure, it can be clearly be seen that during the ISO SWS observations, the [2.77]–[4.175] of every star decreases with the increase of the 2.77 μm band average flux, which indicates that during the central star pulsations $T_{\rm nir}$ decreases and the mid-IR spectra become cooler when the stars become fainter in the infrared, and $T_{\rm nir}$ increases and mid-IR spectra become hotter when the stars become brighter in the infrared. This method is used to trace the change of the color of continua shorter than about 16 μm. The same results also hold.

On the other hand, Whitelock et al. (2006) studied 239 Galactic carbon stars, and from The Midcourse Space Experiment (MSX) that provides survey data at the A-(8.28 μm), C-(12.13 μm), and D-(14.65 μm) bands, they found that the stars with large A-C color indices, i.e. the "red" stars, are all relatively bright in the C bands, particularly for Mira carbon stars. A similar dichotomy is seen in the IRAS data (e.g. Whitelock et al. 2006). Therefore, the continuum evolution during the pulsations of a carbon star seems to be different from the statistical behavior of continuum variations between different carbon stars.

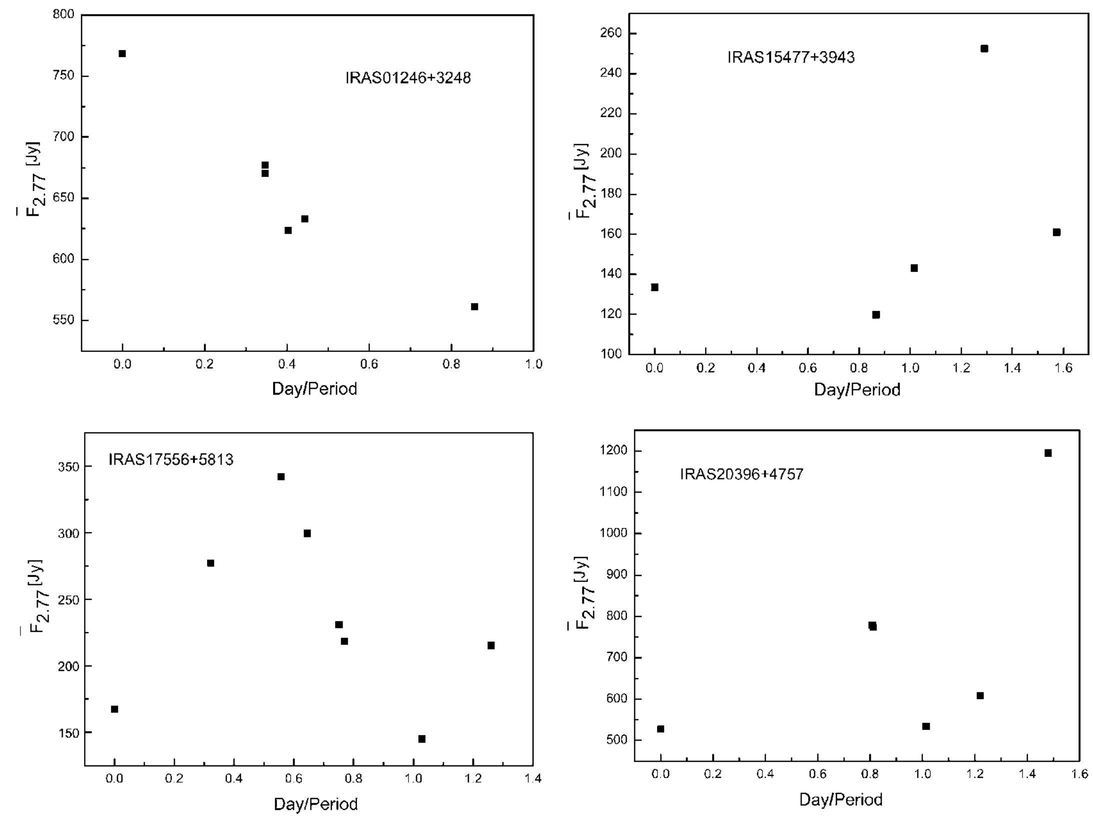

Fig. 2 Variation of average flux of the 2.77 μm band for IRAS 01246+3248, IRAS 15477+3943, IRAS 17556+5813, and IRAS 20396+4757.

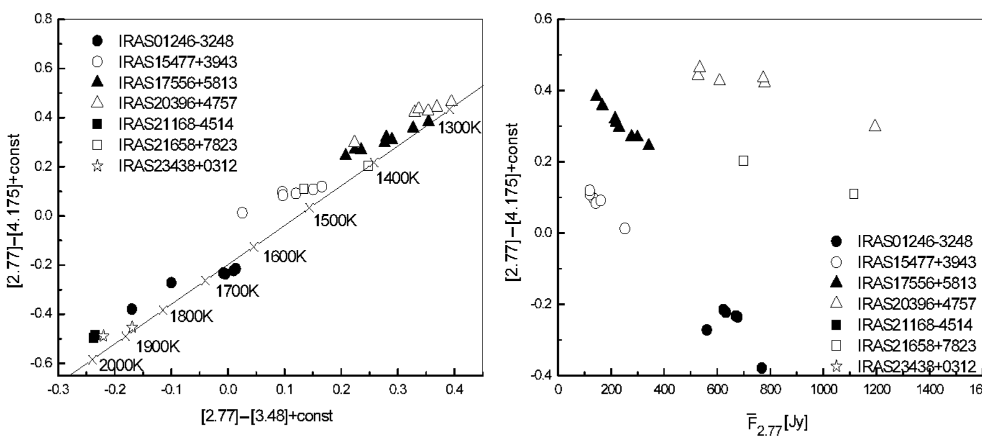

Fig. 3 Color-color diagram of ([2.77]–[4.175])$-$([2.77]–[3.48]) (*left*) and relationship diagram of the [2.77]–[4.175] color and the average flux of the 2.77 μm band (*right*).

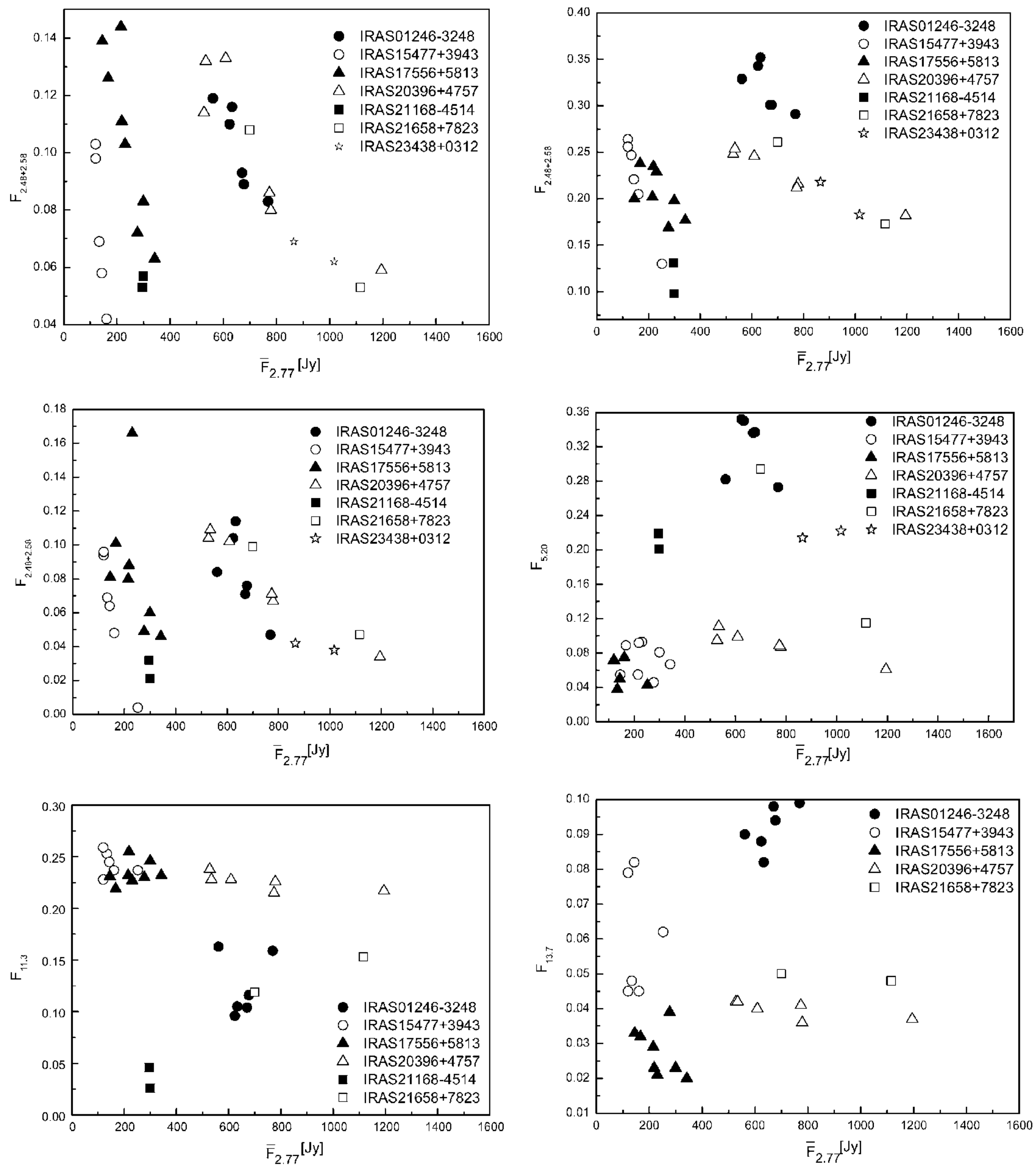

Fig. 4 Relationship diagram between the relative integrated fluxes of the 2.48+2.58, 3.05, 3.90, 5.20, 11.30, and 13.70 μm features and the average flux of the 2.77 μm band.

3.2 The Variation Properties of Spectral Features

Figure 4 plots the variation of the 2.48+2.58, 3.05, 3.90, 5.20, 11.30, and 13.70 μm features with the 2.77 μm band average flux. From this figure, the relative integrated fluxes of the 2.48+2.58, 3.05 and 3.90 μm features, especially for the 2.48+2.58 μm features, anti-correlate with the 2.77 μm band average fluxes for IRAS 01246+3248, IRAS 15477+3943, IRAS 17556+5813 and IRAS 20396+4757. Also, the relative integrated fluxes of the 5.20, 11.30 and 13.70 μm features do not correlate with the 2.77 μm band average fluxes for most of the studied samples except IRAS 20396+4757. It is noted that the shorter the wavelength of the spectral features is, the better the correlation of their relative integrated fluxes with the 2.77 μm band average fluxes is. Therefore, the 2.48+2.58, 3.05 and 3.90 μm features, especially the 2.48+2.58 μm features, can immediately respond to the central star pulsations, while for most of the studied stars, the 5.20, 11.30 and 13.70 μm features do not directly respond to the central star pulsations, although the relative integrated fluxes of the 5.20, 11.30 and 13.70 μm features have variation to a certain extent.

The linear anti-correlation of the 2.77 μm band average fluxes with $T_{\rm nir}$ implies that the 2.48+2.58, 3.05 and 3.90 μm features are stronger in cooler atmospheres during central star pulsations. Temperature plays an important role in the formation of the spectral features and $T_{\rm nir}$ is often seen as a useful indicator of the infrared behavior of carbon stars (e.g., Yamamura et al. 1997).

Yang et al. (2004) pointed out that the relative integrated fluxes of the 3.05 μm feature gradually increase from Group A to Groups B and C (here Groups A, B, and C form a classification system of carbon stars by Yang et al. (2004), see Sect. 3.1), during which $T_{\rm nir}$ gradually decreases; and also pointed out that the relative integrated fluxes of the 5.2 μm feature decrease with a decrease of $T_{\rm nir}$ from Group A to Groups B and C. It is noted that the increase of the 3.05 μm feature in Groups B and C may be due to the carbon stars in Groups B and C having a broader 3.05 μm absorption feature than in Group A. On the other hand, it is also noted that the $T_{\rm nir}$ difference between Group A and Groups B and C is about 1000 K, while for individual stars the $T_{\rm nir}$ difference caused by central star pulsations is about 150 K from Figure 2. This implies that the 5.2 μm feature is not sensitive to small amplitude variations of $T_{\rm nir}$, but the 3.05 μm feature can reflect small amplitude variations of $T_{\rm nir}$.

C_2H_2 shows absorption features at both 3.05 and 13.70 μm, while the variation behaviors of the 3.05 and 13.70 μm features are not similar. The main contributor of the 3.05 μm feature is HCN though the contribution of C_2H_2 is not negligible, while the 13.70 μm feature is almost entirely due to C_2H_2 (Jørgensen et al. 2000). However, the strength of the 13.70 μm feature does not directly reflect the influence of central star pulsations. This may suggest that the formation regime of the 13.70 μm feature is further outside than that of the 3.05 μm feature, which is consistent with the knowledge that the infrared bands are often formed progressively higher up in the atmosphere as the wavelength increases (van Loon et al. 2006; Matsuura et al. 2006).

Similarly, the non-linear change of the 11.30 μm SiC feature with continuum during central star pulsations implies that the evolution of dust envelopes is not in phase with the central star pulsations.

4 CONCLUSIONS

Analysis of spectral variation of seven carbon stars in the infrared, based on ISO SWS spectral data, indicates that during the central star pulsations when carbon stars become fainter in the infrared, their ISO SWS spectra become redder and $T_{\rm nir}$ decreases, or vice versa.

In addition, the 2.48+2.58, 3.05 and 3.90 μm features, especially the 2.48+2.58 μm features, can immediately respond to the central star pulsations, while for most of the studied stars the 5.20, 11.30 and 13.70 μm features do not directly respond to the central star pulsations, although the relative integrated fluxes of the 5.20, 11.30 and 13.70 μm features change to a certain extent.

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