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NEW CANDIDATES FOR CARBON STARS WITH SILICATE FEATURES

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ABSTRACT

All stars in the General Catalogue of Cool Galactic Carbon Stars with *IRAS* 12 μm fluxes greater than 10 Jy were searched for LRS spectra in the *IRAS* LRS data base. Out of the 532 spectra examined, 11 were found to show the 9.7 μm silicate emission feature. Four of these are identified for the first time. This group of carbon stars may represent transition objects between oxygen-rich and carbon-rich stars on the asymptotic giant branch.

Subject headings: infrared: sources — stars: carbon

1. INTRODUCTION

Evolved stars on the asymptotic giant branch (AGB) are often divided into two groups: oxygen-rich or carbon-rich. AGB stars are classified as M type if they show oxygen-based molecular bands (e.g., TiO, VO), or C type if they show carbon-based molecular bands (e.g., C_2) in their photospheric spectra. The M and C spectral classifications correlate very well with circumstellar classifications based on the presence of the 9.7 μm silicate grains (M stars) or 11.3 μm SiC grains (C stars). There is virtually no overlap between M and C stars for excess atoms of the more abundant element are believed to be tied up in CO, a very stable molecule.

However, a number of carbon stars have recently been found to show the silicate emission feature in their circumstellar spectra (Little-Marenin 1986; Willems & de Jong 1986). A more careful study of these objects by Lloyd Evans (1990) showed that among the 20 carbon stars that have been suggested in the literature to have silicate features, 13 are misclassified or misidentified. At present, there exist at least seven stars that are identified as carbon stars based on their photospheric spectra and yet have oxygen-rich circumstellar dust envelopes. Such anomalies can arise from binary systems consisting of both M and C stars (Little-Marenin 1986), or these peculiar stars can represent transition objects from M to C stars (Willems & de Jong 1988). A debate on these alternatives was recently given by de Jong (1989) and Zuckerman & Maddalena (1989).

An interesting element in this controversy is that two (BM Gem, V778 Cyg) out of the seven C stars observed to have silicate features are known ^{13}C-rich J stars (Yamashita 1972, 1975), three (CCGCS 2011,[1] CCGCS 2406 = Mc 79 − 11, CCGCS 3935 = FJF270) are found to be J stars by Lloyd Evans (1990), and the remaining two (CCGCS 4222 = NC 83, EU And) could also be J stars (Lambert, Hinkle, & Smith 1990). This coincidence with J stars is not expected in the binary hypothesis, and lends strength to the possibility that J stars could be transition objects between M and C stars.

In view of the significant implications of this hypothesis on our current understanding of stellar evolution and nucleosynthesis, we have searched for additional C stars that show the silicate feature. In this paper, we report the identification 4 new candidates of C stars that show the 9.7 μm silicate feature in their *IRAS* low-resolution spectra.

2. LRS SPECTRA OF CARBON STARS

Our search is based on the General Catalogue of Cool Galactic Carbon Stars, 2d Edition (Stephenson 1989, hereafter GCCGCS). Out of 5987 sources in the GCCGCS, 3412 have associations in the *IRAS* Point Source Catalog (Version 2, 1988, hereafter PSC), including 11 sources with 2 *IRAS* associations. The criterion for *IRAS* association is based on a 90″ search radius, which is the same as the *IRAS* PSC used in searching for the first edition GCCCS catalog. The *IRAS* low-resolution spectrometer (LRS) covers the spectral range between 8 and 23 μm, and usually records spectra with good signal-to-noise ratio for sources with point source 12 μm fluxes greater than 10 Jy. Among the 3412 GCCGCS/*IRAS* sources, 532 have 12 μm fluxes greater than 10 Jy. We have examined the LRS spectra of these 532 sources in the Atlas of Low-Resolution *IRAS* Spectra (1986, hereafter LRS Atlas) and in Volk & Cohen (1989) for sources with $F_\nu(12\ \mu m) > 40$ Jy; and in Volk et al. (1991) for sources with $F_\nu(12\ \mu m)$ between 20 and 40 Jy. Spectra for sources with $F_\nu(12\ \mu m)$ between 10 and 20 Jy were extracted from the *IRAS* LRS data base at the *IRAS* Data Analysis Facility at the University of Calgary.

A majority (412 out of 532) of the GCCGCS/*IRAS* sources shows the 11.3 μm SiC emission in their LRS spectra. These stars are classified under Group C in the scheme of Volk & Cohen (1989). Ninety of the sources show featureless spectra, and are classified as belonging to Group S (stellar) or Group F (featureless). Of the remaining 30, nine show the 9.7 μm silicate feature in emission (E), two show evidence of PAH features (P), and 19 are classified as unusual (U) or incomplete (I). The spectra of the nine silicate emission sources are displayed in Figure 1. Also shown in Figure 1 are two other C stars (CCGCS 2406 = Mc 79 − 11 and CCGCS 5848 = EU And) previously known to have silicate emission but have 12 μm flux lower than our 10 Jy cutoff. Seven of the 11 carbon stars in Figure 1 have previously been noted to have silicate emission. Four sources (06017+1011, 11048−6046, 17291−3401, 21566+5309) are new candidates for carbon stars with silicate features found as the result of this search.

3. INDIVIDUAL OBJECTS

Not much is known about the four new C star candidates with silicate features. When the *IRAS* positions of the four

[1] CCGCS are designations for stars in the 2d edition of Stephenson's (1989) catalog. First edition stars are designated as CCCS.

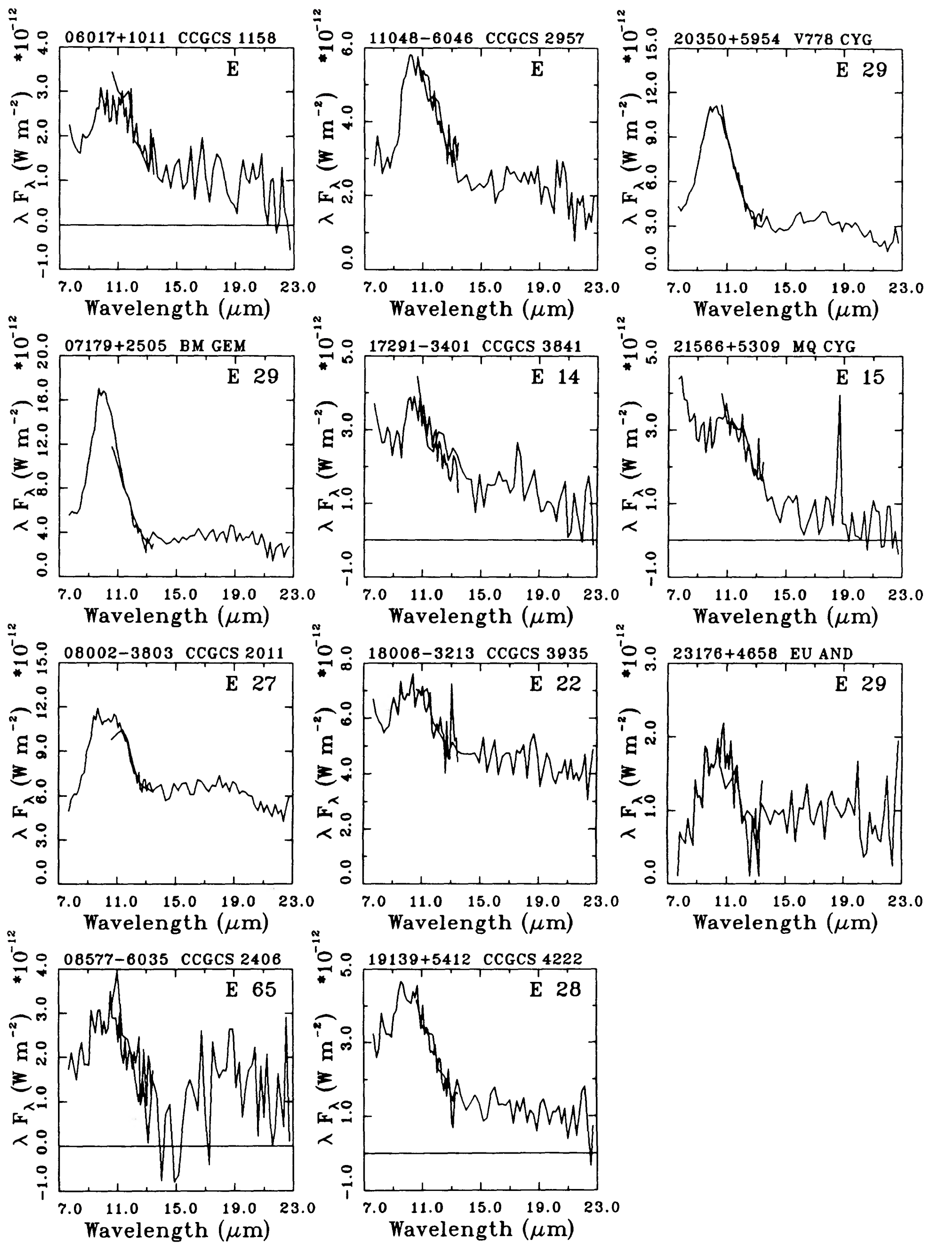

FIG. 1.—LRS spectra of 11 *IRAS* C stars with silicate dust emission feature. The two digit number (when present) on the top right-hand corner of each spectrum is the LRS Atlas classification. All spectra are classified as Group E (silicate emission) in the scheme of Volk & Cohen (1989). A horizontal line is drawn at zero flux level for the spectra that have negative flux values.

sources are checked against the *HST* Guide Star Catalog (1989), we found that three of the four optical sources are located within the *IRAS* error ellipses. The star CCGCS 2957 is not in the Guide Star Catalog and its GCCGCS position is 30″6 away from the *IRAS* PSC position.

In order to better define the photospheric continuum levels, infrared photometry was obtained for 11048−6046 and 17291−3401 using the InSb photometer and Ge bolometer at the 4 m telescope of Cerro Telolo Inter-American Observatory.[2] The observations were kindly obtained for us by Darren DePoy on 1991 February 2. The derived magnitudes are given in Table 1. H_2O and CO indices were also obtained for 11048−6046 with filters at 2.20 μm (continuum), 2.00 μm (H_2O), and 2.36 μm (CO). These indices are also given in Table 1.

The near-infrared photometry measurements together with guide star catalog magnitudes of these four stars are plotted in Figure 2. Also plotted are *IRAS* photometric measurements (corrected for color). The LRS have been corrected for baselines and the two bands are joined together using the method described in the IRAS Explanatory Supplement (1988). The LRS are then normalized with the 12 μm flux after convolving with the 12 μm instrumental profile. We can see that all objects have significant infrared excesses and the visible and infrared

[2] The Cerro Telolo Inter-American Observatory of the National Optical Astronomy Observatories is operated by the Association of Universities for Research, Inc., under contract with the National Science Foundation.

TABLE 1

GROUND-BASED NEAR INFRARED PHOTOMETRY

	OBSERVED MAGNITUDES[a]							
IRAS NAME	J	H	K	L	M	N	H_2O	CO
11048−6046...............	6.86	5.12	4.25	3.39	3.23	1.10	0.31	0.22
17291−3401...............	...	...	...	2.02	2.33	1.17	...	...

[a] Uncertainties are 0.02 mag for JHKL and the molecular indices, and 0.05 mag for M and N.

measurements cannot be fitted with one single Planck function. Such broad energy distributions are typical of carbon stars with silicate features, and can be modeled by emission from dust shells detached from the photosphere (Chan & Kwok 1991).

The four new candidates will now be discussed individually.

06017+1011 (*CCGCS 1158, CCCS 447*).—The LRS of CCGCS 1158 shows a broad emission feature at 10 μm that is similar to CCGCS 2011 (08002−3803). It has a *V* magnitude of 10.3 and an *I* magnitude of 7.6 (Stephenson 1989). This star has been independently suggested as a candidate for carbon stars with silicate features by Noguchi et al. (1990) based on its large 25 μm excess. Near-infrared photometry has been obtained by Noguchi et al. (1990) and their measurements are plotted in Figure 2.

11048−6046 (*CCGCS 2957, CCCS 1818*).—This is object W65−10 in Westerlund's carbon star catalog (Westerlund 1971). The position of this object is outside the *IRAS* error ellipse and is ~31″ away from the *IRAS* position. The high H_2O index found in this object would seem to indicate that it is an M star, although red galactic carbon stars could have an H_2O index as high as observed here (Cohen et al. 1981).

The peak of the 9.7 μm silicate emission feature for 11048−6046 is not as flat as for CCGCS 1158. This object has good *IRAS* fluxes only in the 12 and 25 μm bands.

17291−3401 (*CCGCS 3841, CCCS 2452*).—Both the 9.7 μm

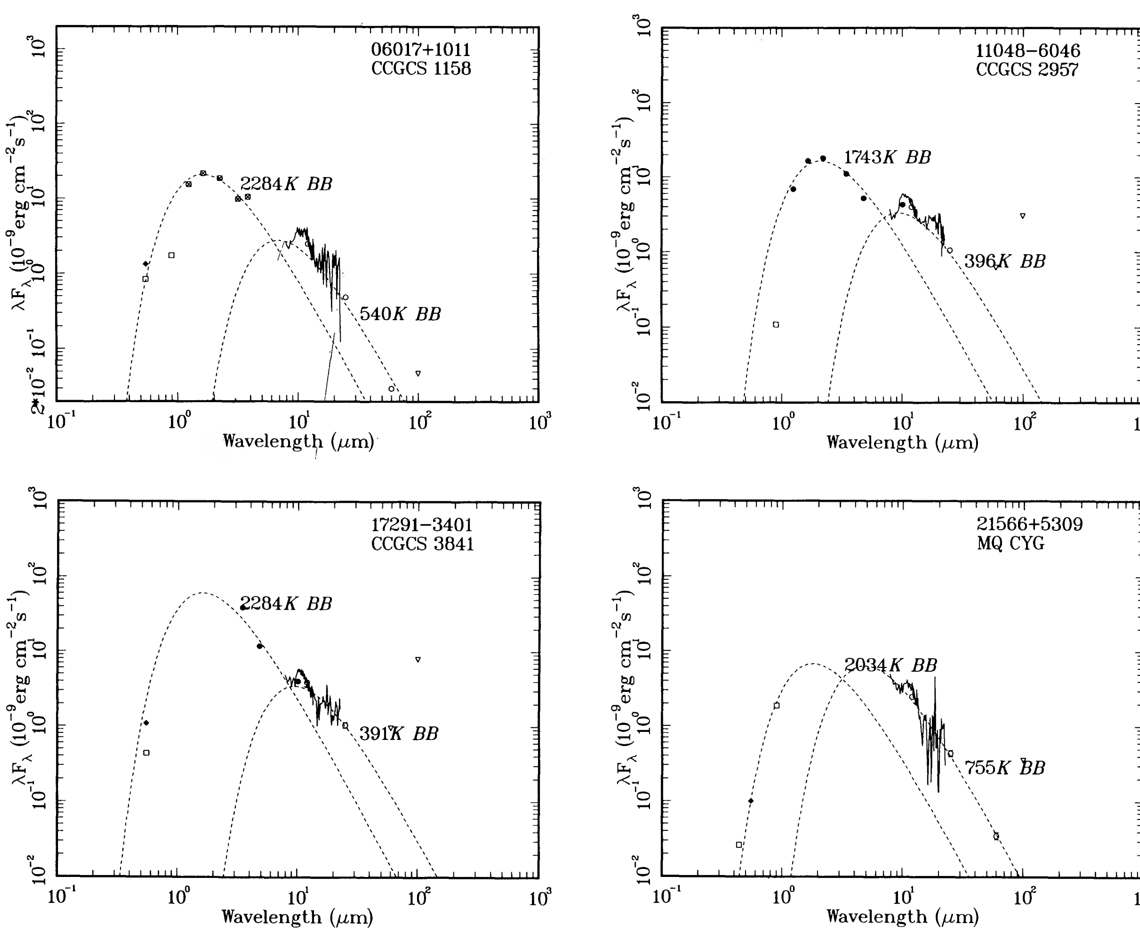

FIG. 2.—Energy distribution of CCGCS 1158, CCGCS 2957, CCGCS 3841, and MQ Cyg. The squares are optical photometric measurements and the diamonds are from the *HST* Guide Star Catalog. The near-infrared (1–5 μm) photometry measurements for CCGCS 2957 a d CCGCS 3841 are from this paper, and data for CCGCS 1158 are from Noguchi et al. (1990). None of the above measurements have been corrected for reddening. The circles are color-corrected *IRAS* photometry, and the inverted triangles are *IRAS* upper limits. The curves between 7 and 23 μm are the *IRAS* LRS normalized to the 12 μm photometry point after convolution with the 12 μm filter profile. The two dashed lines in each diagram are blackbody curves drawn to illustrate the possible levels of the photospheric and dust continua.

and 18 μm silicate features are present in emission. The classification of 14 by the LRS Atlas is therefore likely to be a mistake. This object has a visual magnitude of 11.7, and have good *IRAS* fluxes only in the 12 and 25 μm bands.

21566+5309 (*CCGCS 5526, CCCCS 3095, MQ Cyg*).—Its LRS is classified by the LRS Atlas as class 15. There is an emission feature between 10 and 13 μm which appears too wide to be considered as SiC. The peak of the feature is also slightly longward the expected position of 10 μm for silicate. We have examined the individual scans of this object in the LRS data base. The peak of the feature is at ~ 10 μm in one scan and is at ~ 11 μm in another. The narrow feature at ~ 18 μm is the result of a spike in a single scan and is almost certain to be spurious.

MQ Cyg is a Mira variable of spectral type C(N) with a period of ~ 400 days. This object is located near the blackbody line in the *IRAS* color-color diagram, which makes it similar to other infrared carbon stars (Chan & Kwok 1990). There is a chance that the observed feature is due to SiC and not silicate, although the width of the feature is wider than typical SiC features. This is the only object among the four candidates that the E classification is not definite.

4. NATURE OF CARBON STARS WITH SILICATE FEATURES

While it is possible that some of these objects are binary systems with two AGB stars, one oxygen-rich and the other carbon-rich, in orbit around each other (Little-Marenin 1986), it is argued on statistical grounds that the binary hypothesis is unlikely to apply to all carbon stars with silicate features (de Jong 1989). Since both stars are present in the binary model, the spectra of the optical carbon star and optically obscured M star should cross over in the near-infrared region. However, the near-infrared spectra of some of these C stars with silicate features (BM Gem, V778 Cyg, EU And, CCGCCC2011, and CCGCCC2406) are found to be dominated by CN and CO bands as well as the 3.05 μm C_2H_2 and HCN features with no sign of the M star (Skinner, Griffin, & Whitmore 1990; Noguchi et al. 1990).

The alternative hypothesis proposed by Willems & de Jong (1988) suggests that these objects represent transition objects between mass-losing M stars and C stars. In this model, the silicate feature arises from the remnant of the circumstellar dust envelope ejected during the oxygen-rich phase. As the photosphere changes from oxygen-rich to carbon-rich, mass loss stops and the remnant envelope disperses into the interstellar medium. Emission from this envelope will give rise to the 60 μm excesses observed in most visual carbon stars (Thronson et al. 1987). Quantitative calculations based on this model were able to successfully fit the energy distribution of 123 carbon stars (Chan & Kwok 1988).

The dust component of the four C stars discussed here have color temperatures in the range of 390–750 K (Fig. 2). This is consistent with the suggestion that the dust emission originates from a recently detached oxygen-rich circumstellar envelope. A detailed model of the fitting of the energy distributions of C stars with silicate features will be treated in a separate paper.

5. CHRONOLOGICAL SEQUENCE OF CARBON STAR EVOLUTION

If we accept the Willems & de Jong (1988) model of carbon stars with silicate features, we can construct an evolutionary sequence of carbon star evolution that explains both the photospheric and circumstellar properties of carbon stars. After the detached oxygen-rich dust shell has expanded and cooled, the optical and near-infrared spectrum of the star will be dominated by the carbon-rich photosphere, and the envelope only manifests itself in the far-infrared in the form of 60 μm excesses. These carbon stars will have featureless LRS spectra and their circumstellar spectral type will be S or F (see § 2). As more carbon is dredged up, SiC grains will form, and mass loss can commence again. This corresponds to the optical carbon stars with SiC features (e.g., GCCGCS stars having Group C LRS spectrum). Later, as the mass loss rate increases, the dust envelope can obscure the photosphere, leading to infrared carbon stars with strong SiC features with faint optical counterparts (Chan & Kwok 1990). The high mass-loss rates of these infrared carbon stars can remove the entire hydrogen envelope and terminate the AGB evolution, independent of the termination of AGB by mass loss from oxygen-rich stars (Kwok & Chan 1990; Bryan, Volk, & Kwok 1990).

6. CONCLUSIONS

Using data from the *IRAS* LRS, we have identified three probably and one possible candidates of carbon stars with circumstellar silicate emission. Including seven objects that have been previously noted, there are almost a dozen of these objects known. There is still a possibility that the carbon stars and the *IRAS* sources are only positional coincidences and are not really associated with each other. However, the sample is getting too large for this to be true in all cases. This group of objects demands a consistent explanation for the observed chemical discrepancy, which is not predicted by classical AGB evolutionary models.

The mostly likely interpretation is that the silicate emission arises from the remnant of the circumstellar envelope of an M star which has recently become carbon rich in the photosphere as the result of dredge-up induced by thermal pulses. This is followed by a phase of evolution with little or no mass loss. During this period, the infrared spectrum of carbon stars will be dominated by photospheric emission, and the only evidence for circumstellar emission is in the far-infrared. When mass loss begins again based on SiC grains, the circumstellar spectrum will be dominated again by dust emission. In terms of circumstellar classification, the sequence of evolution for carbon stars is: $E \rightarrow S$ (or F) $\rightarrow C$.

The above scenario gives a consistent explanation to the photospheric and circumstellar properties of all carbon stars. If this model is correct, then this group of carbon stars with silicate features will be important objects to study the chemical transition. Since a significant fraction of these stars is J stars, it is possible that J stars, not S stars as traditionally assumed, are the transition objects between M and C stars.

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