An analysis of the emission features of the IRAS low-resolution spectra of carbon stars

Y. Baron¹, M. de Maizier²,³, R. Papoular¹, and B. Pégourié¹,²

¹ Service d’Astrophysique, CEN Saclay, F-91191 Gif sur Yvette Cedex, France
² Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands
³ Observatoire de Paris, Section de Meudon, F-92195 Meudon, France

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Summary. The Low-Resolution Spectra (LRS) data in Class 4n reveal a considerable wealth of features and a remarkable variety of behaviours of the mid-IR spectra of C-stars. The main thrust of this work is on the SiC feature at 11.3 μm, whose shape and intensity were studied in detail. The feature becomes stronger and narrower as the temperature of the underlying continuum increases. The narrowest features are quite similar in shape to the mass absorption spectrum of laboratory α-SiC. A new weak feature at 11.7 μm may be due to solid SiC₂ or α-C: H. When the whole range (8–23 μm) of the LRS is considered, evidence is found for crystalline as well as amorphous carbon in the emitting dust; the proportion of the former with respect to the latter increases with the dust temperature. The “unidentified” 7.7 and 8.6 μm emission bands are detected at the highest temperatures. A large number of weak SiC features are also found in LRS class 1n; the proportion of C-rich to O-rich giants in the LRS is hence increased to an estimated 60%.

Key words: galaxies: stellar content – infrared radiation – interstellar medium: dust – stars: circumstellar matter – stars: late-type.

1. Introduction

An excellent opportunity to study the mid-IR spectrum of carbon stars is provided by the catalog of Low-Resolution Spectra (LRS) obtained by the Dutch instrument aboard the Infra Red Astronomical Satellite (IRAS) (Wildeman et al., 1983). Indeed, 542 spectra in this catalog clearly display the SiC (silicon carbide) feature at ≈11.3 μm and have been included in class 4n (Olson, 1985). Less conspicuous SiC features can also be found in other classes, especially in 1n, which contains the so-called featureless spectra. By comparison, one of the most recent and thorough study of the circumstellar SiC emission features observed from earth only includes a dozen stars (Cohen, 1984).

The large number of “SiC” spectra now available makes it possible, with suitable statistical procedures, to extract detailed information on the shapes and intensities of this feature and even their correlation with other stellar parameters. This is done here along lines similar to those of a previous paper (Gal et al., 1986; Paper I) devoted to the silicate features in the LRS catalog.

Section 2 defines and explains the statistical indicators used to describe sub-classes of objects of interest and their spectra. It is found that the feature strength, η, is the most suitable discriminant; that is why its distribution is studied first (Sect. 3). The shape of the 11.3 μm feature attributed to SiC, is analyzed in Sect. 4, and compared with laboratory measurements. This provides evidence for structures, on both sides of the feature, which are discussed in Sect. 5. Section 6 determines the characteristic temperature (or slope) of the continuum underlying the SiC feature, which is attributed to a pervasive dust population in the CS envelope; its correlations with the other spectral properties are analyzed. Section 7 describes the galactic distribution of 4n objects and their characteristics. Finally, Sect. 8 uncovers the existence of a clear SiC signature in the “featureless” class 1n of the LRS.

2. Statistical indicators

Since the rationale behind our methods was already detailed in Paper I, it is only necessary here to define the statistics we used to characterize the spectra and their dispersions.

For each spectrum, j, the discrete flux densities \( F(\lambda_j) \) are first normalized to the flux density at \( \lambda_0 \approx 8 \) μm. We then compute the geometric average of the normalized spectra, \( \bar{F}(\lambda_i) \), of a given group of N objects, at each wavelength:

\[
\bar{F}(\lambda_i) = \left( \prod_{j=1}^{N} F(\lambda_j) \right)^{1/N}
\]

To assess the degree of significance of the average normalized spectrum, \( \bar{F} \), we also compute a sample (geometric) standard deviation, \( \Sigma_\lambda(\lambda_i) \), defined as the exponential of the corresponding standard deviation of \( \ln[\bar{F}(\lambda_i)] \). For identical spectra, \( \Sigma_\lambda = 1 \). In cases where the noise component is small, or can be accounted for, \( \Sigma_\lambda - 1 \) gives a measure of the dispersion of the overall spectral profile of the objects in the sub-class under consideration.

We characterize the noise component by the standard deviation, \( \sigma_{\bar{F}}(\lambda_i) \), of the quantity:

\[
D_2(\lambda_i) = F(\lambda_{i+1}) \cdot F(\lambda_0)/F^2(\lambda_{i+1})
\]

Send offprint requests to: R. Papoular

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This is a sensitive indicator of the “roughness” of a curve, since it is directly related to the curvature:

\[ D_2(\lambda) \approx 1 + \left[ (d^2 F/d\lambda^2)^2 \frac{A^2}{F} \right], \]

where \( A = \lambda_{i+1} - \lambda_i \). It is easily shown that the standard deviations of random fluctuations of \( F(\lambda) \) and \( D_2(\lambda) \) are related by

\[ \sigma_{D_2} \approx \frac{\sigma_F}{D_2} = \sqrt{6} \frac{\sigma_F}{F} \]  \hspace{1cm} (3)

so that \( \sigma_{D_2}(\lambda) \) is a measure of the relative intensity of noise in \( F(\lambda) \). While \( \tilde{F}_1 \) characterizes relatively broad (\( \approx 0.3 \mu m \)) features of a group of objects, a “fine structure” (\( \approx 0.3 \mu m \)) superimposed upon those, would show up as a systematic local variation of \( D_2(\lambda) \), the arithmetic mean of \( D_n(\lambda) \). Such a systematic pattern can be due either to real narrow features in the source spectrum, or to residual errors in instrumental calibration. A hint to the presence of the latter is given by the following observation. Consider the \( D_2(\lambda) \) of objects of class 1n (supposedly featureless), with \( F(10 \mu m) > 2 \times 10^{-12} \text{ W m}^{-2} \text{ cm}^{-2} \) (so that the incidence of noise is minimal); there appears to be a reproducible structure, extending over 2 or 3 w.l. intervals, with an amplitude of up to 5%, which is significantly larger than the corresponding standard deviation of the mean, \( \sigma_D(\lambda) \). It might be due to residual calibration errors, since it does not change from one class of objects to another among the classes 1, 2 and 4, which are large enough to allow significant statistics. The excess due to SiC is so small that this additional small structure is sufficient to produce a conspicuous (\( \approx 5\% \)) corrugation on its profile. We have assumed that this is of entirely instrumental origin, and adopted a mathematical smoothing of the spectra to reduce both noise and narrow instrumental features; for this purpose, we used a running average over 3 consecutive wavelengths.

The definition of a group of objects is somewhat arbitrary. For each interesting property of the spectra in class 4, for instance, we have defined sub-classes according to some adequate parameter, the range of which was tailored so that each sub-class was large enough to ensure proper averaging out of the noise, while retaining a sufficient degree of homogeneity. Most sample sizes are \( > 50 \).

The main spectral properties to be studied here are the strength and shape of the 11.3 \( \mu m \) emission feature. The latter is defined as the excess (over the continuum) attributed to silicon carbide in the CS envelope:

\[ F(\lambda) = C(\lambda) \]

Here, the underlying continuum, \( C(\lambda) \), is approximated by a power law, tangent to the lower part of the spectrum \( F(\lambda) \), on both edges of the peak. An inspection of spectra of class 4n suggests that the two wavelengths of tangency are \( \approx 9.7 \) and \( \approx 14 \mu m \), for the class as a whole. The emissivity of SiC is neglected outside this interval.

For reasons stated above, all wavelengths and corresponding flux densities in Eq. (4) are averaged over 3 successive values in the catalog data. The relative excess is defined as \( \delta(\lambda) = \delta(\lambda)/(\lambda) \) and the feature strength, as \( \delta_0 = \delta(11.3 \mu m) \).

In order to characterize the shape of the feature, designated by \( S(\lambda) \), one can think of \( E(\lambda)/\delta_0 \) or \( \delta(\lambda)/\delta_0 \). We tried both and found no qualitative differences. In this paper, we use \( \delta(\lambda)/\delta_0 \) because this choice:

1) enhances the visibility of an auxiliary, narrow feature at 11.7 \( \mu m \) observed here for the first time (Sect. 4).
2) leads to a better agreement of \( S(\lambda) \) (for a particular subclass of 4n objects) with the relative opacities of laboratory samples of SiC.

However, a caveat is in order should the discussion encompass a wavelength band broader than the 4 \( \mu m \) or so covered by the SiC band, as is the case in Sect. 5. This can be qualitatively appreciated as follows. Let the continuum have a temperature \( T_\infty \), so that \( C(\lambda) \propto B_\lambda(T_\infty) \), where \( B_\lambda \) stands for Planck's law. Let \( \varepsilon(\lambda) \) be the emissivity of the SiC shell, which is assumed to be optically thin (as confirmed by the discussion in Sect. 4) and have an equivalent uniform temperature \( T_\infty \). Then

\[ \delta(\lambda) = E(\lambda)/C(\lambda) \propto \frac{\varepsilon(\lambda) \times B_\lambda(T_\infty)}{1 \times B_\lambda(T_\infty)} \]  \hspace{1cm} (5)

If \( T_\infty \) and \( T_\infty \) are both of the order of 1000 K, \( S(\lambda) \approx \varepsilon(\lambda)/\varepsilon(\lambda) \), which is equal to the relative opacity of the dust material. But the departure from this ideal situation becomes more serious as the excursion of \( \lambda \) and the difference of temperatures increase, all the more so since \( C(\lambda) \), here, is approximated by a power law.

Because of noise, we shall not consider individual shapes but averages, \( \overline{S}(\lambda) \), over sub-classes of objects, as was done for the flux densities. However, since the shapes do not differ widely, we will use, here, arithmetic rather than geometric averages (see discussion in Paper I).

3. The strength of the 11.3 \( \mu m \) feature: \( \delta_0 \)

Figure 1 represents the feature strength for each object of class 4n, as a function of \( F_8 = F(8 \mu m) \). It ranges from \( \approx 0.05 \) to \( \approx 3 \). The lower and left parts of the cloud of points are bounded by the selection criteria for this class of objects (Olnon, 1985). When the class is subdivided in sub-classes spanning small ranges of \( F_8 \), it is found that the average strength, \( \bar{\delta}_0 \), is approximately constant (\( \approx 0.35 \)) for \( F_8 > 10^{-12} \text{ W m}^{-2} \text{ cm}^{-2} \). For \( F_8 < 10^{-12} \), \( \delta_0 \) increases progressively up to \( \approx 0.85 \) at \( F_8 = 2 \times 10^{-13} \), mainly due to the effect of selection. The dispersion in each sub-class is

![Fig. 1. The feature strength, \( \delta_0 \), for the objects of class 4n, as a function of the flux density at 8 \( \mu m \), \( F_8 \), in \( \text{W m}^{-2} \text{ cm}^{-2} \). \( \delta_0 \) is the relative excess at \( \lambda = 11.3 \mu m \).](image-url)
measured by the standard deviation of \( \sigma_0(\sigma_0) \) and increases from \( \approx 0.12 \) at \( F_8 = 2 \times 10^{-11} \) to \( \approx 0.45 \) at \( F_8 = 4 \times 10^{-13} \), then decreases to \( \approx 0.3 \) at \( 2 \times 10^{-13} \). While the latter decrease is most probably due to selection effects, it seems that the dispersion of the underlying population of objects increases (in absolute value as well as relative to \( \sigma_0 \)) as \( F_8 \) decreases. Finally, at least, for \( F_8 \geq 10^{-12} \), where selection effects are small, the distribution of \( \sigma_0 \)'s is roughly Poissonian, as is the case for the silicate features of class 2n (Paper I).

### 4. The shape of the 11.3 \( \mu \)m feature

The shape \( S(\lambda) \) is a function of the strength \( \sigma_0 \). Figure 2a shows the arithmetic average shape, \( \bar{S}(\lambda) \), for sub-classes covering different ranges of \( \sigma_0 \) (there are only 2 spectra with \( \sigma_0 < 0.1 \)). Figure 2b shows the dispersion, \( \sigma_S(\lambda) \), of the most inhomogeneous sub-class, \#1. Within the “SiC” band (9.5 to 14.5 \( \mu \)m), each sub-class is homogeneous enough (\( \sigma_0 < 30\% \)) for the average shape to be significant. A clear trend is apparent; as \( \sigma_0 \) decreases, the red wing of the profile inflates to such an extent that even the peak is displaced from \( \approx 11.3 \) to \( \approx 11.7 \) \( \mu \)m. The blue wing, on the other hand, is hardly affected. Figure 3 shows \( \bar{S}(\lambda) \) for the 86 brightest 4n-objects (\( F_8 \geq 5 \times 10^{-12} \); no constraints on \( \sigma_0 \)), a likely representative of features observed from the ground. This is quite close to the average of the 8 features observed by Cohen (1984, Fig. 11). The dispersal is less than 25\% within the SiC band.

Also plotted is the normalized mass absorption coefficient measured by Borghesi et al.

(1983) for crystalline SiC grains of irregular shape with an average size of \( \approx 0.8 \) \( \mu \)m. This feature is distinctly narrower than the LRS feature. On the other hand, it is much closer to the narrowest, “triangular”, LRS feature (the dashed line in Fig. 2a, which is an average over the strongest features of class 4n (\( \sigma_0 \geq 1 \)), except that the latter has no shoulder at 10.2 \( \mu \)m and the wavelength of the maximum (11.3 \( \mu \)m) is shorter by 0.1 \( \mu \)m.

As to the other profiles of Fig. 2a, they may, perhaps, be likened to the “rectangular” (flatter-topped and broader) excesses displayed by Cohen (1984, Fig. 13; see his discussion). Such a variety of shapes has been observed in Y CVn and V CrB by Goebel et al. (1980, 1981) and could be due to grain size and shape effects (Treffers and Cohen, 1974, Fig. 3). A test of this conjecture would require the knowledge of the IR refractive index of SiC, which does not seem to be available. Efforts are presently being made to deduce it from the absorption coefficient by use of Kramers Kronig’s-relations. However, Borghesi et al.

(1983) have already noted that the peak absorptivity shifts to the red as the sample grain size increases.

Note that curves 1 and 2 of Fig. 2a display a distinct bump at \( \approx 11.7 \) \( \mu \)m, narrower still than the SiC feature. This is also
the wavelength assigned by Weltner and McLeod (1964) to the $v_1$ fundamental Si-C stretching band of SiC$_2$, which, in the laboratory, is a major vaporization product of solid SiC above ≈2000 K. We show in Sect. 6 that the “average” CS temperature is much lower than this, especially in sub-classes 1 and 2. If any SiC$_2$ exists, it may therefore condense; this is a necessary condition for the 11.7 μm bump to be ascribed to SiC$_2$, since CS molecules are not usually observed in emission and have much narrower features. As a further argument in favour of this assignment, we recall that the Merrill-Sanford bands of gaseous SiC$_2$ were indeed detected by Stephenson (1973) in the violet spectrum of several carbon stars. However, another possible assignment (α-C:H) is considered in Sect. 5.

In any case, the presence of bumps and peaks on the curves of Fig. 2a seems to exclude large optical depths and lend credence to the assumption that $S(\lambda)$ is nearly proportional to the emissivity of the dust (a large optical depth would give rise to a smooth black-body spectrum insensitive to the dust emissivity). Also, the absence of shoulders on the feature wings is an indication of amorphous and fluffy particles, since these shoulders are attributed to resonances, characteristic of sharp grain boundaries and regular atomic lattices (Huffman, 1977).

5. Other features in the IR excess

Figure 2a displays a conspicuous peak below 10 μm and suggests an upward turn of $S(\lambda)$ beyond 14 μm. Consider first the band between 8 and 10 μm, where the regularity of the trends is remarkable. On going from sub-classes 1 to 5, as the average strengths, $\sigma_0$, increases, the bump at 8.75 weakens progressively; the standard deviation of the bump strength, $\overline{S}$, measured at 8.75 μm, as given by $\sigma_0(8.75)/\sqrt{N}$ (where $N$ is the number of objects in the sub-class), is always smaller than $S(8.75)$, indicating a statistically significant excess for each class.

These trends are confirmed by the average flux density distributions, $F(\lambda)$, of the 5 sub-classes (for the sake of clarity, only 3 of these are shown in Fig. 4). Moreover, the positive curvature in the 14 μm region of Fig. 4 (upward turn beyond 14 μm) becomes increasingly conspicuous as $\sigma_0$ increases. This is better illustrated in Fig. 5, by the average excess spectra for 2 extreme

![Fig. 4. Average energy distributions for 3 sub-classes covering different ranges of feature strength, $\sigma_0$: 1: 0.1 to 0.2 (67 objects); 3: 0.3 to 0.4 (97 objects); 5: 0.6 to 1 (78 objects). Each average has been smoothed by taking averages of $F(\lambda)$ (Eq. 1) over 3 successive wavelengths. Note the variation of the continuum slope between 10 and 14 μm, the bump at ≈8.5 μm and the upward turn beyond 14 μm, increasingly marked from sub-classes 1 to 5. The 3 sub-classes are practically coincident with sub-classes 1, 3 and 5, respectively of Fig. 2a. Data are not reliable beyond 23 μm]

![Fig. 5. Extended average shapes, $\overline{S}(\lambda) = (\overline{E}(\lambda)/\sigma_0)$, for 2 sub-classes: 1: 0.1 ≤ $\sigma_0$ < 0.2 (67 objects), full line; 5: 0.6 ≤ $\sigma_0$ < 1 (78 objects), dashed line. Discontinuity at 13 μm: same as fig. 2a]
subclasses; although the spectra are quite noisy beyond \(15 \mu m\), the trend is clear enough.

The last sub-class of Fig. 2a, \#6, was intentionally left out up to this point in the discussion because of the particular behavior of its excess spectrum near \(8 \mu m\): the bump in this region increases quickly with \(\delta_9\) to reach unmatched levels, after having nearly disappeared (for sub-class 5); moreover, it peaks near \(8.3 \mu m\), instead of \(8.75\) in the previous sub-classes. It must therefore be of a different origin. The \(8.3\) and \(8.75\mu m\) features described here seem to correspond respectively to “a broad feature between \(7\) and \(9 \mu m\)” and “a narrow feature centered at \(8.8 \mu m\)”, which were detected by Willems (1986) in a number of individual LRS spectra.

The origins of all these structures are not obvious. If the emissivity of SiC is considered as negligible in these ranges, then these structures must be traced back to departures of the continuum \(C(\lambda)\) from the assumed power law. These can be due either to features in the emissivity \(e_\nu(\lambda)\) (see Eq. 5), and/or, to a lesser extent, to a departure of the ratio of Planck’s laws from a power law.

Consider first the band between \(8\) and \(10 \mu m\). It is not likely to be an artefact due to silicate absorption at \(\approx 9.7 \mu m\) since this should also perturb the blue wing, which is, in fact, the most stable characteristic of the SiC \(11.3 \mu m\) feature. Silicon oxides are known to have strong bands near \(9 \mu m\), which can be shifted by perturbation due to nearby atoms in a solid lattice. As an example, sillimanite (a \(Al_2SiO_3\) polymorph) has a strong absorption at \(8.3 \mu m\) (Farmer, 1974); but these materials tend to occur preferentially in oxygen-rich envelopes (Huffman, 1977).

It is not likely either to be the feature at \(8.6 \mu m\) which is part of a family of so-called “unidentified” infrared emission features. Indeed this \(8.6 \mu m\) feature always appears as a shoulder on the long wavelength edge of the \(7.7 \mu m\) feature, a much brighter element of the family (Muizon and Habing, 1985; Cohen et al., 1986; Muizon et al., 1986).

Perhaps the best present candidate is the weak, broad bump observed by Koike et al. (1980) between \(6\) and \(10 \mu m\), in the extinction spectrum of amorphous carbon grains in the laboratory. Note that hydrogenated amorphous carbon (a-C:H) deposited in the laboratory (Dischler et al., 1983), also exhibits a medium-wide absorption feature at \(\approx 8 \mu m\), and has, moreover, a solid-state feature just below \(12 \mu m\), which is reminiscent of the \(11.7 \mu m\) bumps on curves 1 and 2 of Fig. 2a. At any rate, it appears that the CS feature is linked with the dust which produces the underlying continuum, for its average strength, \(\delta_{8.75}\), varies only by a factor \(\approx 2\) around 0.6, for sub-classes 1 to 5. This feature is visible for instance in T Lyr, which was classified by Stephenson (1973) as Np.

As regards the distinct behaviour of sub-class 6 near \(8 \mu m\), it should be recalled that some samples of \(x\)-SiC were shown by Borghesi et al. (1983; 1986) to display a narrow dip at \(\approx 9.5 \mu m\) in their absorption spectrum, which could produce a similar appearance.

However in this case, it is more likely that we are seeing the “unidentified” bands at \(7.7\) and \(8.6 \mu m\), mentioned but rejected earlier. Indeed, the “blue” bump in spectrum \#6, Fig. 2a, is quite similar to the “unidentified” features in the spectra of HD44179 (Russel et al., 1978), of the Orion Bar (Aitken et al., 1979), of NGC 7027 (Russel et al., 1977), and in the average flux distribution of LRS class 8n (obtained by us, using the procedure described in Sect. 2). The latter contains mainly compact H II regions and planetary nebulae. On the other hand, of the 24 objects of our sub-class 6, 9 are not given any association by the LRS catalog, only 1 is associated with a PN, but 8 have a possible association with a cool carbon star. The latter type of association fits better with the general slope of the average flux distribution of this sub-class (Fig. 6) and with the presence of a dominant SiC feature at \(11.3 \mu m\), distinctly broader than the “unidentified" \(11.3 \mu m\) feature (usually conspicuous in PNs).

The upward turn at \(\approx 14 \mu m\), in some of the spectra of Figs. 4 and 5, is also interesting. It may be related to the unidentified emission feature discovered by Forrest et al. (1981) in a number of carbon stars and planetary nebulae, longwards of \(24 \mu m\). Here, however, the early upturn of the excess curves is more reminiscent of the broad bump at \(\approx 30 \mu m\) in the absorption efficiency spectrum of graphite grains (Draine and Lee, 1984).

Figure 5 shows that the intensity of this “feature” is anti-correlated with that of the 8.75 feature (for \(1 < \delta_9 < 3\)). This is consistent with an association of the latter with amorphous carbon and of the former with crystalline carbon, for Sect. 6 will show that these features are respectively associated with “high” and “low” ambient temperatures.

6. The continuum color temperature

Figure 7 is a colour-colour diagram for sub-classes 1 to 5 (Fig. 2a) of class 4n, between \(8\) and \(14 \mu m\). The 3 wavelengths used here (8, 9.7, 14 \mu m) were chosen so as to characterize the underlying continuum, \(C(\lambda)\). If a black-body line is drawn on this diagram, the cloud of points is found to be centered at \(\approx 1000\) K and cover a range of colour temperatures from \(\approx 500\) K to \(\approx 3000\) K. However, detailed modeling of observed CS shells around carbon stars (Rowen-Robinson et al., 1983) shows that their overall spectrum can be reproduced using dust of emissivity \(e_\nu \propto \nu^{-1}\) and maximum temperature (at the inner shell radius) of 500 to 1000 K. In most cases, the shell is optically thin at \(\approx 12 \mu m\) (see also Jura, 1986) but the central star is too small and cool to dominate the flux density. If this is also the case for our sample of objects, an estimate of the CS temperature can be gained by drawing in Fig. 7 a representative line for a surface of emissivity \(\propto \nu^{-1}\) and various temperatures. This line is seen to cross the cloud of points right through its middle, where the temp-

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temperature is \( \approx 500 \text{ K} \), and the range of temperatures covered is about 300 to 1000 K. While this is a rather reasonable temperature range, the dispersion of points perpendicular to the line is ascribable to noise, particularly on \( F_{9,7} \) and \( F_{14} \); it decreases when fainter objects are excluded.

By setting a lower limit to \( F_8 \), for instance, at \( 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1} \), it is possible to demonstrate a positive correlation between the continuum temperature and the \( \text{SiC} \) feature strength (Fig. 8). This correlation is difficult to understand without an adequate treatment of the chemistry and thermodynamics of the \( \text{SiC} \) condensation; anyway, it helped us to recognize the correlations between the dust temperature and the intensities of the secondary features, that were alluded to at the end of Sect. 5, since these secondary features are themselves correlated with the main (SiC) feature.

In these respects, too, sub-class 6 behaves in a qualitatively different way. For most of these objects, it is not possible to define a colour temperature with the 3 w.l.’s used above: in the colour-colour diagram of Fig. 7, their representative points wander towards the upper left. Similarly, in a diagram of colours (25 \( \mu\text{m}/60 \mu\text{m} \)) vs (12 \( \mu\text{m}/25 \mu\text{m} \)), they wander to the lower left; this is the behaviour reported by Willems (1986) for the semi-regular or irregular variables in his sample of \( C \) stars.

It is tempting to conclude that our sub-class 6 contains a large proportion of irregulars; this conjecture is supported by the observation of Forrest et al. (1975) that the 11.3 \( \mu\text{m} \) feature strength is particularly strong in irregular \( C \) stars (e.g. UU Aur, Y CVn; the average strength for our sub-class 6 is even stronger). They also note that their spectra indicate little, if any, excess continuum (see also Walker, 1980), in contrast to the cooler C-rich Mira variables, which are veiled by a continuum due to CS dust. If this anticorrelation between feature and continuum strengths also applies to our whole sample, it would mean that the optical thickness of the continuum decreases from sub-classes 1 to 6.

On the other hand, radiative transfer models (Rowan Robinson et al., 1983) show that the temperature at the inner edge of the CS shell tends to be higher for smaller shell optical depths. This indicates that dust temperature increases from subclasses 1 to 6, which favours the annealing of carbon into graphite, as conjectured at the end of Sect. 5.

Since this effect must be strongest in sub-class 6, the presence of the broad graphite feature around 30 \( \mu\text{m} \) should show up most strongly in this case. This may explain the particularly marked and early upturn of the corresponding average energy distribution beyond 15 \( \mu\text{m} \) (Fig. 6).

If the concentration of graphite becomes large enough, it can even distort the continuum under the \( \text{SiC} \) feature, which could explain the excursion of representative points in the colour-colour diagram from the blackbody curve, as noted above.

If it is accepted, on the basis of the above argument, that the continuum is emitted by an optically thin mixture of amorphous and crystalline carbon, and the 11.3 \( \mu\text{m} \) feature by a thin shell of \( \text{SiC} \), then it is possible to estimate the relative amounts of these materials in that thin shell of CS dust. Let \( M_c \) and \( K_c(\lambda) \) be the total mass and mass absorption efficiency of a dust component \( x \), and let \( x = a, c \) or \( x = c \) for the above three components, respectively. At 11.3 \( \mu\text{m} \), according to Eq. 5 and assuming \( T_2 \approx T_c \),

\[
\delta_0 = \frac{\varepsilon(\lambda)}{\varepsilon_c(\lambda)} (K_c M_c + K_a M_a) = \frac{(K_c M_c + K_a M_a)}{1 + \left(\frac{K_c M_c}{K_a M_a}\right)}
\]  

(6)

At \( \lambda = 8.75 \mu\text{m} \), the relative intensity of the bump in \( K_c(\lambda) \) (Koike et al., 1980; Borghesi, 1983) is \( \Delta K_c(\lambda)/K_c(\lambda) \approx 0.2 \). If this is the origin of the LRS feature at 8.75 \( \mu\text{m} \), then, the strength of this feature can be written as:

\[
\delta' = \frac{\Delta K_c(\lambda) M_c}{K_c M_c + K_a M_a} = \frac{(\Delta K_c(\lambda) K_c M_c)}{1 + \left(\frac{K_c M_c}{K_a M_a}\right)}
\]

(7)

Now \( K = (3/4\rho) \cdot Q/a \), where \( \rho \) is the mass density of the dust material, \( a \) the radius and \( Q \) the absorption efficiency of the grains. Hence, \( \rho = 2, 2.2 \) and 3.2, respectively (Hodgman et al., 1955). From Koike et al. (1980), \( (Q/a) \approx 10^4 \text{ cm}^{-1} \), while \( (Q/a) \approx 2 \times 10^3 \text{ cm}^{-1} \) for \( a = 0.3 \mu\text{m} \), from Draine and Lee (1984), near

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As regards sub-class 6, most of these objects are very faint $(F_{\nu} \lesssim 10^{-12} \text{ W m}^{-2} \text{ m}^{-1})$ and mostly found towards the inner galactic plane; their small $\sigma_b$ may simply reflect their large distance. But their identification as irregulars (Sect. 6) is consistent with a small distance from the plane (Walker, 1980).

8. The SiC feature in LRS class In

Evidence for the SiC features can be found in class In (so-called “featureless”) albeit at low levels. We have limited our search to $F_{12} \gtrsim 30 \text{ Jy}$, or $6 \times 10^{-13} \text{ W m}^{-2} \text{ m}^{-1}$, restricting our sample to 445 objects out of 2246, so as to exclude the most noisy spectra. In a colour-colour plot like that of Fig. 7, this sub-class itself subdivides into two quite distinct clouds of points: a) one set tightly grouped around $(\log(F_{8.7}/F_{12}) = -0.32$, $\log(F_{14}/F_{8.7}) = -0.66)$; the spectroscopic and photometric data of IRAS show that, from 8 to 60 $\mu$m, these nearly have a black-body spectrum (as expected for photospheres), and their colour temperature is $\approx 4000 \text{K}$; b) another set, more loosely grouped along the black-body line and covering the range $(\log(F_{8.7}/F_{12}) = -0.09$ to $-0.12)$, $(\log(F_{14}/F_{8.7}) = -0.54$ to $-0.43)$. For the latter set, the corresponding temperatures range from $\approx 400$ to $\approx 700 \text{K}$, similar to the cooler part of the “4n” set of Fig. 7. Clearly, these objects have dust shells.

If we apply to these “In” groups the procedure used above to extract the IR excess and the 11.3 $\mu$m feature strength, $\delta_{11.3}$, we find no regular feature, but only apparently random noise, for group (a) from 8 to 23 $\mu$m. Not so for group (b): Fig. 9 presents the average shapes for two sub-groups covering different ranges of $\delta_{11.3}$. The SiC feature is obvious, but it differs in some respects from the features of class 4n (cf. Fig. 5): 1) it is wider at half-maximum and extends from $\approx 9$ to $\approx 15 \mu$m; 2) it has a shoulder or bump about 13 $\mu$m (but its shape is difficult to ascertain, because of the instrumental discontinuity at this point; cf. Fig. 2); 3) the bump about 8.5 $\mu$m is much less conspicuous.

Also, for this group (b), there is no apparent anti-correlation between $\delta_{11.3}$ and $F_{14}/F_{8.7}$, like the one displayed in Fig. 8 for class 4n. Finally, this group is completely randomly distributed in galactic longitude and more broadly distributed in latitude than subclass 1 of class 4n (see table 1); the std. dev., $\sigma_b$, is 25.6$^\circ$ for $1 \lesssim \delta_{11.3} < .15$ and 17.1$^\circ$ for $\delta_{11.3} \geq .15$.

Thus, roughly speaking, group (b) behaves, in important respects, like sub-class 1 of class 4n but there are intriguing differences, which may be due, in part at least, to the different selection criteria involved. It might be preferable in this case to examine each individual spectrum, i.e. using the LRS database rather than the LRS catalog. One of the most conspicuous differences, the bump at $\approx 12.8 \mu$m, may be linked with the new emission feature observed in some LRS spectra characterized by strong 7.7 and 11.3 $\mu$m features (Cohen et al., 1985; Muizon et al., 1986): this comprises a plateau from 11.3 to 13 $\mu$m and a small peak at about 12.6–12.8 $\mu$m.

One may wonder if the increased width of the average feature in Fig. 9, and the deficiency shortward of 9.7 $\mu$m are not due to “pollution” of the sample by oxygen-rich stars which could have escaped the selection process for inclusion in class 2n. This is not likely, however, for the following reasons. Consider IRAS objects in class 2n with $F_{12} > 30 \text{ Jy}$ (same range of brightnesses as group (b) here). These objects are found to have, at $\approx 10 \mu$m, an average relative excess $\delta_{10} \sim 2 \pm 1$ (std. dev.), as shown in

---

**Table 1**

<table>
<thead>
<tr>
<th>Subclass</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_0$</td>
<td>0.1–0.2</td>
<td>0.2–0.3</td>
<td>0.3–0.4</td>
<td>0.4–0.6</td>
<td>0.6–1.1</td>
<td>1–3</td>
<td>All</td>
</tr>
<tr>
<td>No. of objects</td>
<td>67</td>
<td>128</td>
<td>96</td>
<td>142</td>
<td>78</td>
<td>24</td>
<td>535</td>
</tr>
<tr>
<td>$\delta_0$ (deg.)</td>
<td>15.1</td>
<td>10.4</td>
<td>11.9</td>
<td>11.2</td>
<td>10.7</td>
<td>5.8</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Note. Lists of objects are available from the authors on request.

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Fig. 9. Average shapes, $\bar{S}(\lambda) = \frac{\sigma(\lambda)}{\sigma_o}$ for 2 sub-classes of 1n. Full line: 79 objects with $0.1 < \sigma_o < 0.15$; dashed line: 43 objects with $\sigma_o \geq 0.15$. All have $F_{12} \geq 30\,\text{Jy}\,(6 \times 10^{-13}\,\text{Wm}^{-2}\,\text{um}^{-1})$. There are no objects with $\sigma_o \geq 0.3$ and only 14 beyond 0.2. The discontinuity at $\sim 20.5\,\mu\text{m}$ in the full line is due to spurious signals in only 2 objects.

Fig. 6a of paper I; hence, only a small minority of bright M-stars can be expected to escape the selection test for the silicate feature and remain in IRAS class 1n. Such objects were searched for in group (b) by adding the constraint $\sigma(8.5\,\mu\text{m}) \leq 0$. The objects that are eliminated in this way (about 1/4 of the sample) are found to have an average spectrum quite similar to $\neq 1$ of Fig. 5. The average spectrum of the remaining objects is very similar to those of Fig. 9 except for the strengthening and narrowing of the peak at $12.8\,\mu\text{m}$, and the increased deficiency shortward of $9.7\,\mu\text{m}$. This spectral profile bears no resemblance to that which is obtained by applying to the 2n objects the algorithm used here to derive $(\sigma/\sigma_o)$.

Thus, it is difficult to escape the conclusion that the objects considered here have carbon-rich envelopes. If they are indeed C-giants, then the proportion of these with respect to O-giants is much larger than the simple ratio of populations of classes 4n and 2nU6n in the LRS catalog $(542/(1738 + 78) \approx 0.30)$. For, if we assume that the fraction of C-stars in the whole class 1n is the same as in our sample of 445 bright objects (0.275), the number of such stars is expected to be $\approx 610$ and the ratio of carbon-to-oxygen-rich giants becomes $\approx 0.63$. This is much larger than the corresponding ratio for irregulars and semi-regulars (0.38) or for LPV's (0.15) in the Sun's vicinity (Allen, 1963; p. 212, 213); but it is in agreement with the recent analysis by Zuckerman (1986) of a sample of 110 IRAS stars. Note that this ratio is strongly correlated with metallicity and is known to vary from $\sim 10^{-3}$ in the galactic nuclear bulge to $\sim 1$ in the LMC and $\sim 20$ in the SMC (Scalo, 1981). The objects of our group (b) are found preferentially near the galactic plane (like 4n objects) and towards the anti-center.

9. Conclusion

Our work has revealed a considerable wealth of features in, and a variety of behaviours of, the mid-IR spectra of carbon stars. This was made possible by considering average spectra of tens of similar objects. Our findings may be summarized as follows:

1. The strength of the circumstellar SiC feature in the LRS spans the range from $\approx 0.1$ to $\approx 3.5$. It is positively correlated with the temperature of the dust which produces the underlying continuum.

2. The shape of the feature varies regularly with its strength and becomes narrower as the strength increases. The shape of the strongest features is quite similar to the mass absorption spectrum of $\alpha$-SiC; but it has no resonance shoulders on its wings, indicating the SiC is amorphous and the grains fluffy. As the feature weakens a bump grows on its red wing. On top of this bump, a narrower feature, centered at $\approx 11.7\,\mu\text{m}$ grows progressively; it could be due to SiC$_2$ or $\alpha$-C:H (amorphous hydrogenated carbon). The weakest features (to be found mostly in class 1n) have a shoulder or bump at $\approx 12.8\,\mu\text{m}$, which looks like an unidentified emission feature recently discovered in very red nebulae.

3. Beyond $14\,\mu\text{m}$, where the SiC emissivity becomes negligible, the excess curve rises continuously to the red, the more steeply the hotter the temperature of the underlying continuum. This structure may be due to an increasing proportion of crystalline carbon.

4. Below $10\,\mu\text{m}$, two different spectral structures may appear depending on the SiC feature strength: weak SiC features are accompanied, on average, by a bump which peaks at $8.75\,\mu\text{m}$ and has a roughly constant strength above the continuum ($\approx 0.04$...
to 0.08); the strongest SiC features are accompanied by a steep rise towards $8\,\mu m$, similar to the red wing of the “unidentified” 7.7–8.6 $\mu m$ feature.

5. The main constituents of the CS dust appear to be crystalline and amorphous carbon, and SiC, whose proportions are estimated.

6. A large number of weak SiC features are found in LRS class In. The proportion of C-rich relative to O-rich giants (in the LRS) is hence increased to an estimated 60%.

7. In a given range of the SiC-feature strengths, the objects are rather evenly distributed in galactic longitude, the more so the weaker the feature. The strongest features are found only at low latitudes, and are likely to be associated with irregular variables.

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