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CARBON STARS

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RESUMEN. Se considera la clasificación de estrellas de carbono y la naturaleza de los varios objetos incluídos entre ellas. Se tratan problemas como el origen de su opacidad ultravioleta y la relación de la clasificación con la temperatura efectiva y con sus curvas de luz. Se da énfasis a resultados recientes relacionados con sus luminosidades y sus relaciones evolutivas con otros objetos. Se llama la atención a la necesidad de segregar estrellas de tipo N en estudios estadísticos ya que éstas forman un grupo mucho más homogéneo que las estrellas de tipo R.

ABSTRACT. The classification of carbon stars and the nature of various species included among them are reviewed. Emphasis is given to recent results that shed light on problems such as the source of their ultraviolet opacity, how their classification is correlated with effective temperature and variability types, their mean luminosity, and their evolutionary relationship with other objects. Attention is called to the need of limiting statistical studies of carbon stars to those of type N. These include much more homogeneous objects than stars of type R.

Key words: **STARS-CARBON**

I. INTRODUCTION

Henry Norris Russell once said that eclipsing binaries were a royal road to astrophysics because with them one could determine stellar masses and radii and also derive information about limb darkening, departures from sphericity, and even about mass transfer between binary components. However, apart from mean stellar densities, eclipsing stars tell us little about processes in stellar interiors, about stellar evolution, or about mass loss and the enrichment of the interstellar medium. Red giants and in particular carbon stars, are now playing a vital, even a unique role, in advancing our knowledge of these aspects of astrophysics.

Carbon stars are among the coolest yet bolometrically bright objects known. Many carbon stars are variable, some in bizarre ways like the R Coronae Borealis stars, some (the long-period and Mira variables) with fairly regular pulses. They are known to shed mass at rates possibly up to 10^{-4} $M_{\odot}$/yr, sufficient to account, even though they are rare in space, for perhaps up to half the rate of mass being returned to the interstellar medium. They show strontium, barium and other elements that indicate the s-process must take place in their interiors. The cooler carbon stars show unusual isotopic ratios such as extraordinarily high C^{12}/C^{13} ratios indicative not only of 3α thermonuclear reactions but of deep convective episodes capable of bringing C^{12} atoms to the surface. The presence of relatively short lived technetium (lifetime ~ 2 x 10^5 years) shows in addition, that the transfer of C^{12} atoms to the surface must be rapid. Their C/O abundance ratio is >1 while for the M giants it is <1, and in S stars ~ 1.0. This suggests that carbon enrichment results in an M → S → carbon stars evolutionary relationship. They frequently have circumstellar envelopes rich in carbon, and/or

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silicon carbide (Si C) grains that can tell us much about the nature of interstellar dust. They show enigmatic space distributions indicative, possibly, of galactic metallicity gradients.

Knowledge about carbon stars has lately been growing at a fast rate, especially because optical infrared and radio astronomy have provided valuable new insight about their evolution and how they relate to the interstellar medium. Reviewed here are some on-going carbon star problems that have a long historical background, as well as new findings about these stars. Excellent earlier reviews about carbon stars are Bidelman's (1956) which emphasized the variety of objects included among these stars; Wallerstein's (1973), which emphasized some of their physical properties, Alksne's et al. (1983) which emphasized observational data and contains an extensive bibliography, and McClure's (1985) which discussed evolutionary aspects. A catalogue of carbon stars has been published by Stephenson (1973).

II. CLASSIFICATION OF CARBON STARS

The study of carbon stars started in 1867 when Jesuit Father Sechi developed a morphological classification scheme for stellar spectra. Sechi assigned stellar spectra to one of four types; the reddest stars were either type III or type IV. Spectra of these two types show molecular bands but degraded in different directions. The molecular bands in type III stars are now known to be caused by TiO while those in type IV stars were for a long time suspected to be caused by carbon or by some carbon compound partly because Sechi himself found a match of the type IV molecular bands with those from a benzene (C_6H_6) flame, and partly because George Ellery Hale and collaborators at the Yerkes Observatory found an excellent match with the Swan spectrum which had been previously observed in electric light bulbs with graphite filaments developed in 1860 (19 years before Edison) by the English physicist Joseph Wilson Swan. A definitive assignment of the Swan bands to C_2 was not made until 1930.

In preparation for the Henry Draper Catalogue, Pickering (1896) and Williamina Fleming (1912) subdivided Sechi's types I, II, and III stars into the well known Harvard classes B,A,F,G,K,M. Type IV stars were called either R or N, being distinguished by the fact that in N stars the violet spectral continuum is appreciably fainter than in R stars. Fleming remarked however that R and N stars formed a continuous sequence. She also found two unusual stars which she called "R peculiar" (namely T Camelopardis and π^1 Gruis). These turned out to be prototype S stars, which show ZrO bands and were recognized as a special class by Merrill (1922 see also Keenan and Boeshaar, 1980).

C.D. Shane (1920, 1928) subdivided decimally the R and N stars according to the intensity of the violet continuum and found that the intensity of the Swan bands varied in unexpected ways if the increase in faintness of the ultraviolet continuum was interpreted as a decrease in effective temperature. From the decrease of molecular dissociation as the temperature decreases, one would expect a monotonic increase in Swan band intensities when the stars are ordered supposedly by decreasing temperatures as suggested by the weakness of the ultraviolet continuum. Instead, Shane found the Swan band intensity to first increase then decrease and finally to increase again as the ultraviolet continuum intensity decreased among the R and N stars. Shane concluded that some opacity source must contribute to the ultraviolet faintness of carbon stars.

An important finding by Shane (1920) was that in some carbon stars the λ4737 Swan band head was accompanied by one at λ4745 or by one at λ4752. Sanford (1950) showed that these various band heads had isotopic origins as follows: $C^{12}C^{12}$ λ4737, $C^{12}C^{13}$ λ4745, $C^{13}C^{13}$ λ4752. This finding has been followed by numerous studies of isotopic ratios, especially C^{12}/C^{13} which turns out to be ~ 30 Johnson et al. (1982) in N type stars, much higher than the equilibrium value of 3 expected from CNO cycle processing. This result not only indicates 3α processing but an effective rapid outward transport of the C^{12} atoms to prevent CNO processing in outer shells to drive the C^{12}/C^{13} ratio down to the equilibrium value. These findings constitute major observational support for the thermal-pulse dredge-up mechanism proposed to explain asymptotic giant branch evolution (summarized by Iben and Renzini 1983). Lower C^{12}/C^{13} ratios (i.e. 1 to 2) found among the R and other carbon star groups (Fujita, 1980) provide observational constrains in such theories.

Shane's results led Keenan and Morgan (1941) to abandon the idea that in carbon stars the intensity of the violet continuum and the strength of the Swan bands could be reconciled with a continuous temperature gradation. By using temperature sensitive atomic line intensities such as those of the Na D doublet and of Ca I λ4227 and atomic line ratios, they proposed to include the R and N types in a single C-type where the early C stars had the highest temperatures as determined by the atomic lines. R stars turned out to be mostly C0 to C4 stars and N stars C3 or later. In addition, the Keenan-Morgan classes included a subscript (1 to 5) that estimated the strength of the Swan band with head at λ5635. Presumably Swan band strengths depended on abundances and not on temperatures.

Another set of C-types based supposedly on effective temperatures was proposed by Bouigue (1954). Assuming a Boltzmann distribution of molecules among vibrational levels within the same electronic energy state and using theoretically derived transition probabilities, Bouigue obtained a set of effective temperatures which he averaged with temperatures derived empirically from the intensity of the Na D lines. These average temperatures were used to assign decimal C classifications to a set of standard stars. The Bouigue and Keenan-Morgan types did not correlate well. Bouigue remarked that the correlation could be improved if carbon stars that showed at λ6260 a molecular band previously found by Keenan and Morgan, were left out. Bouigue proposed a special subtype "J" for these stars. Gordon (1971) showed that the λ6260 band was a blend that included an isotopic $C^{13}N^{14}$ band and that Bouigue's J-carbon stars showed unusually strong Li I λ6708. Utsumi (1985) finds J stars not to have an enhancement of s-process elements.

Uncertainties in Bouigue's transition probabilities and of the level of the continuum used in estimating vibrational temperatures led several investigators to reestimate effective temperatures by improving the vibrational-temperature method, by using curves of growth, or simply color temperatures. Richer (1971) introduced another C-classification based on near-infrared spectral features, principally the intensity of the CaII triplet at λλ8498, 8543, and 8662 which was known to be a reliable temperature indicator.

Keenan-Morgan C-classes are still in use principally because Yamashita (1972, 1975a) quantified the Keenan-Morgan scheme and assigned Keenan-Morgan classes to a large number of stars that have served as standards. Cohen (1979) has refined Yamashita's quantification and applied his results to carbon stars detected as infrared sources. Such stars are now believed to have circumstellar dust shells resulting from mass loss. How the shells are formed is not entirely clear but a generally accepted explanation (see Salpeter, 1977, Lefevre, 1986) is that in the star's outer layers dust grains may condense from carbon-based gases. Radiation pressure forces the grains outward and they, in turn, drive gas atoms. An interesting finding by Cohen is that the sum of the decimal temperature subclass and the Swan band strength index in the Keenan-Morgan spectral classes is correlated with the mass loss as one would expect if dust grains condensation increases as the temperature decreases and as the amount of carbon increases.

In spite of the efforts to combine the Harvard R, N classes into one temperature related classification, doubts have existed all along whether this was wise or even possible. Wildt (1936) concluded from a comparison of blue and near-infrared spectral intensities that no continuous sequence joining the R, N classes may exist. Eggen (1972) found that in $(R-I)_0$ histograms N stars form an isolated group with $(R-I)_0$ >0.8 while the CH, R, and BaII stars predominantly have $(R-I)_0 < 0.45$. In view of this clear-cut separation Eggen concuded that "the attempt to bridge the R and N classifications with a single C classification may have been a retrogressive step." In addition to such a clear cut color separation, a corresponding one may exist in regard to luminosities (McClure 1985). These differences have led investigators to frequently prefer the old R, N designations rather than C-types. A review of classification criteria by Fujita (1980) illustrates the problems related to the classification of carbon stars.

III. CARBON STAR SPECIES

While developing their classification system, Keenan and Morgan noticed a group of five R-type stars that showed in their spectra unusually strong CH bands and an almost complete absence of atomic lines. Among these stars were found the carbon stars with the three highest known radial velocities. This suggested that among carbon stars one could find species with different kinematic properties. Keenan (1942) designated this group as prototype "CH" stars. CH stars are now known to have enhanced s-process elements. Hartwick and Cowley (1988) have found numerous CH stars in the Large Magellanic Cloud with $M_V \sim -3.5$, on the average. CH stars have also been found in the metal-poor globular clusters M2, M22, M55 and are now considered tracers of the Galactic halo population. CH stars have also been found in the Draco, Ursa Minor, and Sculptor dwarf spheroidal galaxies (Aaronson et al. 1983, Frogel et al. 1982). An important clue regarding the evolution of CH stars is McClure's (1984) finding that most, if not all, CH stars show radial velocity variations indicative of a binary nature. Mould and Aaronson (1986) have presented a schematic evolutionary sequence whereby CH stars are formed in binary systems.

In a classic discussion of "non-typical" carbon stars Bidelman (1956) listed, in addition to CH stars other carbon star subgroups. One of these designated "HdC", includes stars that show abnormally weak CH bands and are now known as members of a larger group of stars called Hydrogen-deficient stars. Practically all stars of this kind in Bidelman's original list are variables of the R Coronae Borealis type whose nearly constant brightness is erratically decreased by up to 8 magnitudes during relatively short periods. O'Keefe (1939, see also Warner, 1967, Fadeyev, 1983, Lambert, 1986; Feast, 1986) suggested that ejected gas condensing into carbon dust clouds that eventually dissipate could explain their light curves. Warner (1967) found HdC stars to be of high luminosity and Richer (1975) assigned them luminosity class Ib. Interestingly, the eponymous star of the group has been found by Gillett et al. (1986) to be surrounded by an ~8 pc diameter dust cloud.

Another "non-typical" group of carbon stars includes the BaII stars (often simply called barium stars) originally recognized by Bidelman and Keenan in 1951. These stars show strong BaII λ4554 and SrI λ4607 lines. McClure et al. (1980, and McClure (1983) have found that all BaII stars are, very likely, members of binary systems. This suggests that BaII stars may have an evolutionary relationship with CH stars. Another carbon star species recognized by Bidelman includes the Lithium carbon stars which show extraordinarily strong LiI λ6708.

Infrared astronomy reveals not only that most carbon stars have circumstellar dust shells but that possibly among them there are previously unrecognized distinct species or at least groups in different stages of evolution. Gillett et al. (1971) found 9 out of 31 observed carbon stars to show excess 5μm flux over that at 3.5μm. Practically all these stars were Mira variables while most of the remaining 22 stars are semi-regular or irregular variables. An analogous result was found by Jura (1983) in comparing 12μm and 2μm fluxes in carbon stars listed as IRAS point sources. Cohen and Schmidt (1982) designate as "Extreme Carbon Stars" (ECS) those whose infrared fluxes indicate thick circumstellar dust shells. All ECS's may simply represent a late stage in the evolution of otherwise "typical" carbon stars. Another group of stars showing some carbon features but not usually included among carbon stars are "Subgiant CH stars" recognized by Bond (1974). According to Luck and Bond (1982) subgiant CH stars may be progenitors of BaII stars.

Some bizarre isolated cases of stars that show Swan bands but that cannot possibly be related to typical giant carbon stars are also known. A curious example is the proper motion dwarf Giclas 77-61 found by Dahn et al. (1977) and shown by Dearborn et al. (1986) to, almost certainly, have a collapsed companion which presumably transferred its carbon-rich outer layers. A number of degenerate stars are also known to show Swan bands (Greenstein, 1970). Such bizarre cases are however rare (Liebert et al. 1979).

It would seem that statistical interpretations of carbon stars would be of little value because these stars are such heterogenous objects. However, the vast majority of known carbon stars do not belong to the special species described above. Also, practically all such species are of early R type in the R,N classification system or C3 or earlier in the Keenan-Morgan scheme. Studies based on N stars, or that favor the later C-types, will include a much more homogenous group of stars than when all stars showing Swan bands are included.

As remarked previously, carbon stars have been found among IRAS point sources. These can be confirmed as carbon stars by the optical or near-infrared detection of Swan or CN bands, by detection of infrared carbon related features, or by radio detection of CO (Sopka et al. 1985). Chan and Kwok (1988) claim that differences exist between carbon stars detected optically and those found by infrared or radio techniques. These differences may represent different evolutionary stages of typical carbon stars. Among optically detected carbon stars are found many objects with relatively thin circumstellar dust shells. Objects with thick circumstellar envelopes are interpreted as losing mass at a high rate and forming carbon or SiC grains. The vast majority of carbon stars detected as IRAS sources are of N type. Carbon stars suffering copious mass loss are believed to be precursors of at least some planetary nebulae. The mass loss rate has been estimated to be as high as 10^{-4} $M_{\odot}$/yr by Knapp and Morris (1985). This could account for up to one half the rate of mass being returned to the interstellar medium in the solar vicinity. Thronson et al. (1987) find that the contribution to the interstellar medium by carbon stars does not depend on their distance from the galactic center. In contrast, the space density of M giants, which are expected to yield silicate dust, depends on galactocentric distance, being higher near the Galactic bulge. It follows that the nature of interstellar dust may vary with radial distance in the galaxy with silicate based dust found preferably towards the center and carbon or silicon carbide dust towards the periphery.

Apart from the various species listed above, there are SC and CS stars with spectral features of both S and C classes. The existence of MS stars and of these intermediate carbon types plus the absence of CM or MC combinations of classes has long been regarded as evidence for an evolutionary relationship between M,S, and C stars. Russell (1934) found that C/O ≤ 1 in M and S stars and >1 in C stars. About 1940 Fujita reasoned that free C and O atoms would most readily form extremely stable CO molecules. After CO is formed excess either carbon or oxygen atoms are available to form other compounds depending on the value of C/O (see Fujita, 1970).

Cameron (1955) found that the Ba, Sr, and Zr features in carbon or S stars could be explained by the formation of certain nuclei through capture of neutrons produced in the $C^{13}(\alpha,n)O^{16}$ reaction of the CNO cycle and subsequently slowed down as thermal equilibrium was reached. Mixing between the core and the outer layers could cause these s-process elements to appear at a star's surface and produce the familiar spectral features of Barium and S stars. Eventual exhaustion of core hydrogen and initiation of 3α reactions would result in a gradual carbon enrichment that caused an M to S to C-type evolution.

Cameron's suggestions were followed by many studies and eventually led to the thermal-pulse dredge-up scenario for the evolution of S and C stars from M ones on the asymptotic giant branch. (See Iben and Renzini, 1983 for a review). Striking observational confirmation of the $M \rightarrow S \rightarrow C$ evolutionary relationship is found in the giant branches of Magellanic Cloud Clusters. Bessell et al. (1983) obtained spectra and JHK magnitudes of bright giant branch members of older SMC and LMC clusters and derived bolometric magnitudes from the bolometric correction and $(J-K)_0$ relationship found by Frogel et al. (1980a). In a number of SMC and LMC globular clusters, the spectra showed in the same giant branches the presence of M, MS and carbon stars. In luminosity the carbon stars were brightest and the M stars the fainter ones. The MS stars fit neatly between these two classes. Frogel and Blanco (1984) found that the luminosity separating the M and C giants in Magellanic Clouds Cluster increases with decreasing cluster ages as expected in the thermal-pulse dredge-up theory of asymptotic giant branch evolution.

IV. EFFECTIVE TEMPERATURES AND BOLOMETRIC CORRECTIONS

The various schemes proposed to classify carbon stars supposedly reflected in part the effective temperatures. The accurate evaluation of these temperatures has proved to be a notoriously difficult task. Based on atomic line ratios Fujita et al. (1968) presented a temperature calibration of the Keenan-Morgan classes up to class C6 and Richer (1971), one based on a calibration by Johnson (1966) of I-L colors in terms of effective temperatures. Richer's results are shown by crosses in Figure 1. The increase in temperature with advancing Keenan-Morgan subtype among late carbon stars led Richer to propose his own classification scheme. Richer's results assumed that Johnson's calibration curve which at the lower temperatures was based on M stars, could be used on carbon stars. Tsuji (1981) applied the so-called infrared flux method proposed by Blackwell et al. (1979). This requires knowledge of an apparent infrared monochromatic flux f_λ and an apparent integrated flux Φ and yields effective temperatures Te and angular diameters by iteration starting from an assumed monochromatic flux F_λ at the stars' surface. Iteration involves the equations:

$$\theta = 2\,(f_\lambda/F_\lambda)^{1/2} \quad \text{and} \quad \Phi = \frac{\sigma\, Te^4}{4}\,\theta^2 .$$

Of course if θ is known, say from interferometry or from lunar occultation observations, the second equation yields Te directly if Φ is known. In Figure 1 are summarized values of Te for individual stars of different Keenan-Morgan classes. Present uncertainties in recent Te derivations are about ±300°K. These uncertainties in part are due to stellar variation and in part to blanketing in the 3μm region generally used to measure fluxes for the infrared flux method. Regardless, an anticorrelation between the Keenan-Morgan types and effective

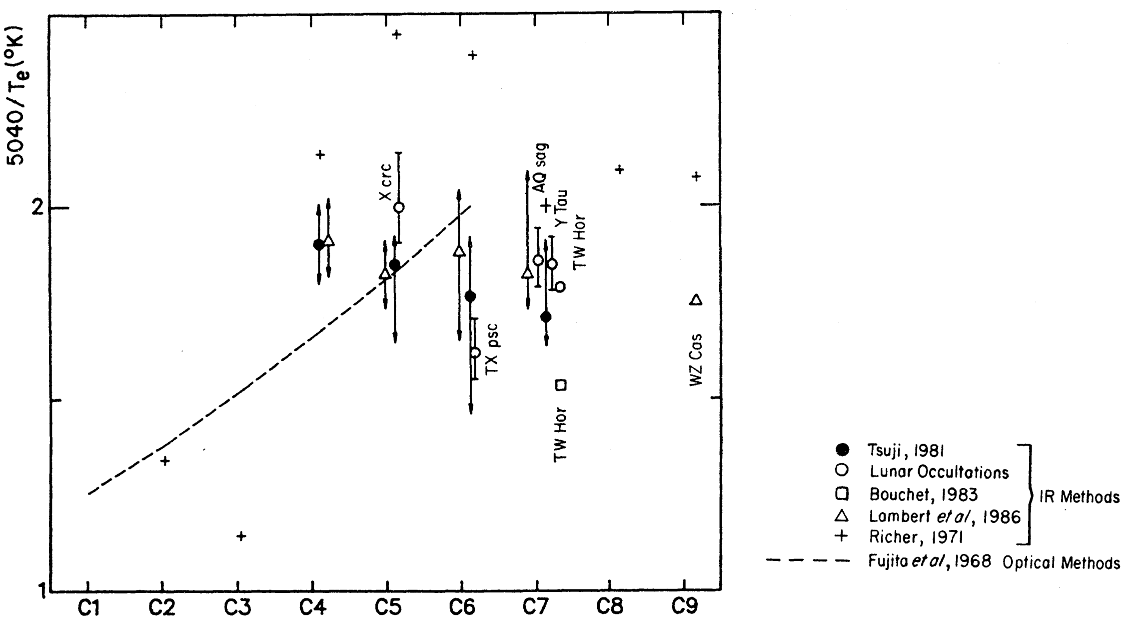

FIG. 1.- Effective temperature calibration of Keenan-Morgan C-types.

temperatures is apparent among the late C stars. Scalo (1973) suggested that opacity due to CN severely affects radiation transfer in the optical regions and the atomic lines that define the Keenan-Morgan classes are not formed in the photospheric level that defines effective temperatures (see also Tsuji, 1985).

Closely related to effective temperatures are bolometric corrections. Apparent infrared integrated magnitudes were obtained by Frogel et al. (1980a) from B,V,R,I,J,K,L photometric data for carbon stars presented by Mendoza and Johnson (1965). Defining a bolometric K correction by $m_b = BC_K + K_0$, Frogel et al. found a tight relationship between BC_K and $(J-K)_0$ values for carbon stars. This relationship has been used to derive absolute bolometric magnitudes of carbon stars in the Magellanic Clouds.

V. THE ULTRAVIOLET OPACITY

As remarked previously, Shane (1920) concluded that the ultraviolet faintness in carbon stars was not entirely due to low temperatures but also to an unknown source of opacity. Identification of that source has turned out to be difficult. McKellar and Richardson (1955) attributed the opacity to gaseous C_3 on the basis of an experimental spectroscopic match. Walker (1976) however, noticed a correlation between ultraviolet faintness and the strength of the Merrill-Sanford bands of SiC_2 at $\lambda\lambda$4868-4979 (Keenan 1956) and suggested SiC grains condensed from the gaseous SiC_2 as the opacity source. Soon thereafter, in 1974, Treffers and Cohen (see also Zuckermann, 1980) found that the infrared continuum of carbon stars with circumstellar envelopes resembles what is expected from graphite or amorphous carbon grains but that a feature at 11.5μm attributed to SiC also appears. Recent IRAS data (see Thronson et al. 1987) favor carbon grains as predominant in circumstellar envelopes. Presumably these are condensed from gaseous C_3. The oxygen-rich M giants with circumstellar envelopes show at 10μm and 20μm the signature of silicates.

A test to differentiate between the two candidates for the opacity source, gaseous C_3 or

SiC grains, was carried out by Bregman and Bregman (1978). These sources may be differentiated because the opacity of SiC grains increases monotonically into the ultraviolet while that of C_3 decreases shortward of λ3900. The results favored C_3 for the brighter stars included in the test but were inconclusive for the fainter ones. Goebel et al. (1978) have confirmed the presence of C_3-related features in the infrared spectrum of the carbon star Y C Vn.

VI. DETECTION OF FAINT CARBON STARS

A technique for discovering faint carbon stars was developed by Nassau and Colacevich (1949). It consists of detection of near infrared CNλλ7945, 8125, and 8320 bands in very low dispersion spectra. These bands are particularly strong among stars with Keenan-Margon C5 to C7 classes (Wyckoff 1970). This method tends to exclude stars earlier than C4 (Blanco and Münch, 1955; Fujita, 1980) and therefore favors the N stars and excludes most non-typical species. The technique has been used in extensive Milky Way surveys by Nassau and collaborators (see Blanco, 1965 for a review) and by Westerlund (1971) and adapted to grism observations with large telescopes by Blanco et al. (1980) for surveying the Magellanic Clouds. Surveys, of faint carbon stars have also been made with a technique pioneered by Sanduleak and Philip (1977) in which the Swan bands at λλ4737, 5165 are isolated in low dispersion spectra. Westerlund et al., (1986) have used this method with a large telescope to survey faint carbon stars. In Magellanic Clouds surveys made with these two techniques, the same stars are frequently identified but some stars are detected only with the infrared technique (presumably the reddest ones) while others are only detected with by the green-yellow Swan bands. Presumably these are the earlier C stars not detectable by the infrared technique (McCarthy, 1987).

These methods and also a photoelectric one in which near-infrared CN bands are detected with a technique developed by Richer et al. (1984) and Aaronson et al. (1986), have been used to detect carbon stars in the Local Group of galaxies.

VII. GALACTIC DISTRIBUTION OF CARBON STARS

The near-infrared technique pioneered by Nassau and Colacevich (1950) was used by Nassau and collaborators, (see Blanco 1965), Blanco and Münch (1955) and Smith and Smith (1956) to carry out surveys that covered a 4°-wide belt along the entire galactic equator. As shown by Nassau and van Albada (1949) this technique is also useful for detection of M type stars. The star counts for carbon and late M giants derived from these surveys show a marked concentration towards the galactic equator. Their longitude distributions are plotted in Figure 2 As explained above this method favors detection of the redder, cooler carbon stars. Thus most of our knowledge of the galactic distribution of carbon stars really refers to classical N types. A marked difference exists in the galactic distribution of M and N giants, one not expected from an evolutionary relationship between these stars. Presumably not all M giants evolve into carbon stars, and those that do not favor the galactic bulge.

The decided preference by M giants for the direction of the galactic center has been confirmed by independent estimates of carbon and M giants space densities by Westerlund (1965), Stephenson (1973), and Fuenmayor (1981). A possible explanation of this finding has been advanced by Thronson et al. (1987). A galactic metallicity gradient related to a decrease of the C/O ratio with distance from the center may cause this effect. Thronson et al. however, find that carbon stars detected as IRAS sources appear not to vary appreciably in space density with galactic radial distance, and that dust enshrouded M giants are far more frequent near the galactic center. Jura et al. (1989) find that the space density of the more luminous (presumably N-type) carbon stars is not significantly lower at 3 Kpc towards the anticenter than near the sun. A radial constancy of carbon stars space densities is not expected from the star counts for carbon stars plotted in Figure 2, although the preference of M giants for the galactic center is in agreement with those star counts and also with deep surveys in Baade's Window by Nassau and Blanco (1958) and Blanco, McCarthy and Blanco, (1984).

VIII. THE C/M RATIO

An early result of the surveys of very faint carbon stars in the galactic bulge and in the Magellanic Clouds was that the number ratio of cool carbon to M giants of subtype M6 or later was $\lesssim 0.001$ in the galactic bulge, ~2 in the LMC and about 20 in the SMC (Blanco et al., 1978;

Blanco and McCarthy, 1983). These striking differences at first sight seem to correlate with mean metallicity values. These are known to be higher in the galactic bulge than in the LMC and higher in the LMC than in the SMC. From counts of carbon stars in the Milky Way and nearby

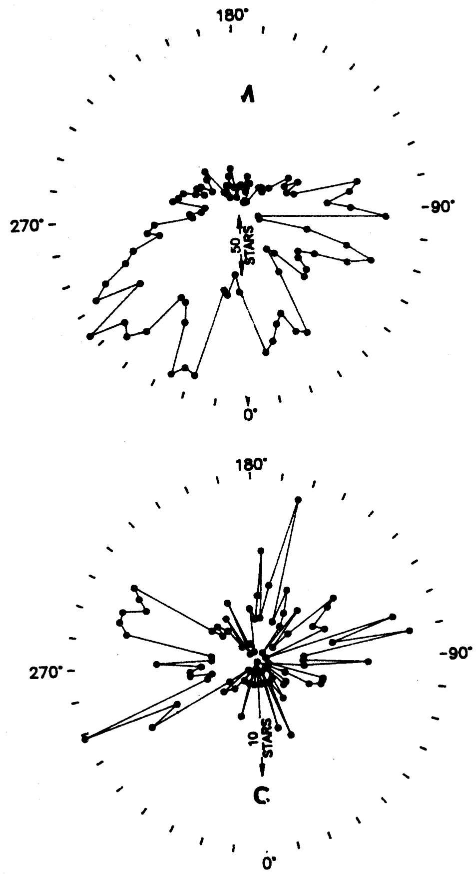

FIG. 2.- Distribution along the galactic equator of the surface density of M giants and carbon stars.

galaxies, Richer and Westerlund (1983) found that in these galaxies the total number of carbon stars per unit galactic mass was correlated with the metallicity while Aaronson et al. (1983) in an intercomparison of carbon stars in seven nearby dwarf galaxies found the number of carbon stars not to be a simple function of parent galaxy luminosity, nor by implication, of metallicity.

Attempts have been made (see Scalo and Miller 1981) to calibrate theoretically the C/M ratios in terms of metallicity alone. However, models of carbon star structures suggest that the C/M ratio may depend on the age as well as the metallicity of stellar populations (Renzini and Voli, 1981; Frogel 1986). Explanation of the strong C/M ratio differences observed in the Local Group of Galaxies remains a matter of some controversy.

IX. THE LUMINOSITY OF CARBON STARS

Early determinations of carbon star luminosities were based on statistical parallaxes supplemented by data from double stars, cluster memberships, the Wilson-Bappu (1957 see also Richer, 1975) effect etc. Gordon (1968) in a review of 6 such calibration methods concluded that for N stars $\langle M_V \rangle = -1.5$ to -3.5 and that R stars are appreciably less luminous. Similar results were obtained by Mikami (1975) in a statistical analysis of proper motions and radial velocities. Baumert (1974) recognizing that a weakness in such determinations were poor photometric data and inclusion of different species in the solutions, collected I(1.04μm) magnitudes for 360 carbon stars and used proper motions and radial velocities to find, statistically, the mean luminosities of various carbon star groups. He found that R stars are about 2.5 I magnitudes fainter than N stars, and that for the latter, $\langle M_I \rangle = -4.3 \pm 0.6$. If V-I(1.04) = 3.9 (Richer, 1971) this converts to $\langle M_V \rangle \sim -0.4$, much fainter than Gordon's and Mikami's results. This discrepancy illustrates the uncertainties in all such early luminosity determinations. The need for accurate luminosity determinations became acute with the detailed theoretical modelling of carbon stars evolution by Iben (1975), Iben and Truran (1978), Renzini and Voli (1981) (see also Iben and Renzini, 1983). A prediction of the theoretical modelling was that for carbon stars $M_{bol} \sim -6.0$ or brighter. A definitive test of the theoretical conclusions became possible when Blanco, McCarthy and Blanco (1980) identified practically complete samples of carbon stars in the Magellanic Clouds. Their technique, namely detection of near infrared CN bands in hypersensitized Kodak IVN plates exposed through a grism that yielded a dispersion of 2350Å/mm, tended to avoid as mentioned earlier, earlier C types thus favoring the classic N-type carbon stars. Richer (1980), Frogel et al. (1980b) and Cohen et al. (1981) derived absolute bolometric magnitudes and luminosity functions for the Magellanic Clouds carbon stars. The LMC-SMC carbon stars turned out to be 1 to 2 magnitudes fainter than expected. Mould and Aaronson (1986) found larger discrepancies in comparisons with stars in local group dwarf spheroidals. These findings led to an intensive exploration of the input physics of the models. Iben (1988) has summarized the efforts made since then to bring theoretical models and observational results in line.

X. VARIABILITY AMONG CARBON STARS

It is well known that carbon stars may vary in brightness. Table I summarizes variability statistics by temperature classes according to Mikami (1978).

TABLE I. Variability Percentages by Temperature Classes

Keenan-Moran-Yamashita	No.	Miras	Semiregular or Irregular	Other	Nonvariable
C 0-3	52	0	4	6	90
C 4-5	134	5	58	1	36
C 6-7	90	22	51	1	26
C 8-9	12	34	58	0	8

Clearly, early C stars are rarely variable and most late C stars are definitely variable; the frequency of large amplitude Mira variables increases with advancing C class. As remarked previously carbon stars with strong far-infrared excesses tend to be Mira variables, a fact that suggests a relationship between the pulses that cause variability and the formation of circumstellar dust shells. When variability statistics among M, S and C type stars are compared, Miras are found to be twice as frequent as the semi irregular or irregular variables among M and S stars while the opposite is true for carbon stars (Alksne and Ikaunieks, 1971).

Lloyd-Evans (1985) has presented statistics of variability for MS, S, SC and C stars with different Swan bands strength indices. These are summarized in Table II.

TABLE II. Variability Statistics from MS to Cx_5

Spectral type	No.	(total)	Irregular	(total)	Semiregular and Mira	(total)	Constant	(total)
S 3-5	136		10		11		79	
S 6-8	71		16		17		67	
SC	30		30		43		27	
Cx_0	5		40		20		40	
Cx_1	16		25		63		12	
Cx_2	22	290	45	53	46	21	9	26
Cx_3	74		42		26		32	
Cx_4	115		63		12		25	
Cx_5	58		60		10		29	

In this table solar neighborhood stars are ordered, presumably according to increasing C/O ratio. The table suggests that variability increases as C/O increases and that irregular variability also increases with the C/O ratio. As pointed out by Lloyd-Evans, however, such statistical summaries suffer from observational biases. The detection of complete samples of carbon M and S stars in the Magellanic Clouds makes possible the derivation in the future of more significant correlations.

Correlations between solar vicinity carbon star luminosities and light-curve features have long been suspected but luminosity uncertainties and errors in light curve classifications have obscured these effects. Such biases are minimized in studies of carbon stars in the Magellanic Clouds. Wood et al. (1983) found LMC and SMC long period carbon stars to show, along with other asymptotic giant branch stars, an increase in luminosity with the periods. (For a review of variability characteristics of red giant stars in general see Querci, 1986).

XI. KINEMATICS

Radial velocities for 427 carbon stars were used by Dean (1976) to solve for solar motion and velocity ellipsoid characteristics of stars divided according to Keenan-Morgan classes into the groups C0-C4, C5, C6 and C7-C9. Divisions by variability type were also made. In view of the heterogeneity of early C types and the relatively small numbers of stars in some of Dean's subgroups, summarized here are only his results for C5 and C6 stars whether variable or not. In their majority these stars are N-types. Both these types yielded similar results, namely a solar motion of about 14 kms s^{-1} towards $\ell \sim 60°$, $b \sim +20°$, and a flattened ellipsoid with galactic-plane axial-dispersions $\Sigma_x \sim 17$ kms s^{-1} towards a vertex at $\ell \sim 20°$, and $\Sigma_y \sim 15$ kms s^{-1} with probable errors about ±2 to ±6 kms s^{-1}, and a dispersion towards $b = 90°$ of about 13 ±36 kms s^{-1} Dean's solar motion although smaller by 1/3, agreed in apex direction with a solution including variables for N stars within 1 Kpc of the sun by Dahn (1964). Dahn's velocity ellipsoid solutions also showed similar features but with somewhat larger Σx, Σy axes and an indeterminate (imaginary) Σ_z dispersion. No reasonably close match exists between these kinematic features, and those listed by Delhaye (1965) for various groups of main sequence stars. There is however a rough similarity with the kinematic properties of main sequence F type stars. If this indicates an evolutionary relationship then the main sequence progenitors of the N stars had masses about 1 to 2 solar masses.

XII. SUMMARY AND CONCLUSIONS

Recent infrared photometric observations and determinations of angular diameters confirm the fact noticed earlier by Richer (1971), among others, on the basis of color-temperatures, that with advancing subtype Keenan-Morgan types C5 or later are anti-correlated with decreasing temperature. In any statistical study of carbon stars careful attention must be given to selecting objects that are as nearly homogeneous as possible. Forming carbon star groups by Keenan-Morgan classes can obscure the fact that such groups, especially those with early C-types, may be rather inhomogeneous. Among stars assigned Harvard R or N classes, the N stars form a far more homogeneous group than the R stars although appreciable variability differences may exist among N stars. Errors in available variability type assignments may have affected published statistical summaries about the variability of carbon stars.

Among on-going carbon star problems whose solution will help us understand better these stars are: the source of their ultraviolet opacity; the input physics one should use in their theoretical modelling in order to match predicted and observed bolometric luminosities; the accurate determination of isotopic ratios and how these relate to stellar interior processes; their precise evolutionary relationship to other objects; how they enrich the interstellar medium; and how is their galactic distribution correlated with their evolutionary stage.

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