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Carbon Stars

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Abstract. In this paper, the present state of knowledge of the carbon stars is discussed. Particular attention is given to issues of classification, evolution, variability, populations in our own and other galaxies, and circumstellar material.

Key words. Stars: carbon—stars: evolution—stars: circumstellar matter —galaxies: magellanic clouds.

1. Introduction

Carbon stars have been reviewed on several previous occasions, most recently by Wallerstein & Knapp (1998). A conference devoted to this topic was held in 1996 (Wing 2000) and two meetings on AGB stars (Le Bertre *et al.* 1999; Kerschbaum *et al.* 2007) also contain much on carbon stars. This review emphasizes developments since 1997, while paying particular attention to connections with earlier work and to some of the important sources of concepts. Recent and ongoing developments include surveys for carbon stars in more of the galaxies of the local group and detailed spectroscopy and infrared photometry for many of them, as well as general surveys such as 2MASS, *AKARI* and the *Sirius* near infrared survey of the Magellanic Clouds and several dwarf galaxies, the *Spitzer*-SAGE mid-infrared survey of the Magellanic Clouds and the current *Herschel* infrared satellite project. Detailed studies of relatively bright galactic examples continue to be made by high-resolution spectroscopy, concentrating on abundance determinations using the red spectral region, and infrared and radio observations which give information on the history of mass loss.

2. The discovery of carbon stars

Surveys of a large area of sky use mass production techniques, of which objective prism spectroscopy has been most widely used. The traditional blue spectral region, covering the Swan bands of C_2 and the violet CN bands, is especially effective for the discovery of the hot R-type carbon stars. The Henry Draper Catalogue (Cannon & Pickering 1918) includes many relatively nearby R and N stars found in this way. Sanduleak & Philip (1977), Hartwick & Cowley (1988), Cowley & Hartwick (1991) and Kontizas *et al.* (2001) found many carbon stars in the Large Magellanic Cloud

(LMC), while Morgan & Hatzidimitriou (1995) found a similar sample in the Small Magellanic Cloud (SMC). The extreme redness of the cooler N stars, as well as the weakness of the characteristic Swan bands of C_2 in some, dictates a move to the red and infrared. The red bands of CN were used in the detection of 302 carbon stars in the LMC by Westerlund *et al.* (1978), of 1707 in the SMC by Rebeirot *et al.* (1993) and of 320 carbon stars in both Magellanic Clouds by Blanco *et al.* (1980). The Hamburg/ESO survey found large numbers of faint high latitude carbon stars, which were identified automatically on digitised Schmidt objective prism plates (Christlieb *et al.* 2001). Goswami (2005) obtained slit spectra of a sample of 91 stars from this survey and identified many CH stars among them; relatively few N stars and no dwarf carbon stars were found. Stars of the latter type were first recognised from their high proper motions (Dahn *et al.* 1977) and their low luminosity was confirmed by trigonometric parallaxes (Dearborn *et al.* 1986; Green *et al.* 1991).

Crowding problems and faintness dictated a move to imaging to detect carbon and M stars in star clusters and nearby galaxies. Crude photometry on the *VI* system permitted the detection of late type stars in the Magellanic Clouds (Lloyd Evans 1978, 1980a) but slit spectroscopy is required to distinguish between M, S and C stars (Lloyd Evans 1980b 1983a; Bessell *et al.* 1983). The APM survey for cool carbon stars in our own Galaxy uses the large $(B-R)$ of such stars to search for them among the many objects measured on UK Schmidt Telescope plates (Totten & Irwin 1998). Red and near-infrared imaging has the advantage that the luminous red stars stand out even before their colours are taken into account. The redder carbon stars may be identified with a high degree of confidence from their $(J-K)$ and especially $(H-K)$ values but there is inevitable confusion with K, M and S stars at the blue end of the colour range (Nikolaev & Weinberg 2000). Cioni *et al.* (2001) show that while all M stars nearly have $(J-K_s) < 1.4$, so do many spectroscopically-identified carbon stars, so that the use of such a limit misses carbon stars and underestimates the C/M ratio.

M and C stars may be distinguished using interference filters to isolate back-to-back bands of TiO and CN near 790.0 nm. The ratio of the intensities in these two wavebands, coupled with a broadband colour such as $(R-I)$, has proved very useful in separating M and C stars (Richer *et al.* 1984; Cook *et al.* 1986; Albert *et al.* 2000).

The low resolution spectrometer on the *IRAS* satellite discovered many bright but previously unsuspected carbon stars by the presence of the 11.2 μm emission band of SiC arising in circumstellar material (Olnon *et al.* 1986).

This revealed for the first time that a high proportion of carbon stars are not seen at all in visible light. Some extreme carbon stars, notably AFGL 3068, have no SiC band but featureless mid-infrared spectra, so that new examples have been sought among *IRAS* objects with similar spectra (Volk *et al.* 1992), at the cost of including occasional stars of other types, such as post-AGB stars, which may also lack obvious bands.

Optical spectra of a sample of extreme carbon stars, discovered in the *AFGL* programme, are discussed by Cohen (1979) and by Cohen & Hitchon (1996), who show that they are Mira variables with periods of 1–2 years and are the carbon equivalents of the OH/IR stars. The Swan bands of C_2 and most of the visible spectrum are often obscured, leaving the CN bands near 780 nm to show that they are carbon stars.

A General Catalogue of Galactic Carbon Stars, initiated by C. B. Stephenson at the Warner and Swasey Observatory, is now in its third edition (Alksnis *et al.* 2001). Stephenson (1984) provided a similar catalogue of S stars, with potential overlap in the area of CS and SC stars.

3. Spectral classification and temperature determination

The R stars may be subdivided into several groups. The classical R stars have normal or near-normal compositions apart from the enhanced carbon abundance and enhanced ^{13}C (Dominy 1984; Zamora *et al.* 2009). The CH stars (Keenan 1942) are metal deficient high velocity stars with enhanced abundances of the s-process elements. The Hydrogen deficient carbon stars (HdC) are characterised by the absence or extreme weakness of the Balmer lines and of CH. The majority of those known are R Coronae Borealis variables (RCB), whose spectacular fadings account for most of their discoveries; the non-variable HdC stars are only revealed by their spectra. ^{12}C/^{13}C is generally large, as the isotopic bandheads are usually weak or absent (e.g., Lloyd Evans *et al.* 1991; Pollard *et al.* 1994), indicating values of ^{12}C/^{13}C up to several hundreds (Fujita & Tsuji 1977), but V CrA is an exception, with ^{12}C/^{13}C of about three (Rao & Lambert 2008). The dwarf carbon stars generally have a pronounced break in the spectrum at the 619.1 nm band of C_2, which combines with weak CN to give a distinctive spectral appearance (Green *et al.* 1992). Keenan's (1993) classification scheme for the R stars is of doubtful validity, as the features used as luminosity criteria are sensitive to composition.

R stars are distinguished from N stars by their relatively strong violet continuum (Cannon & Pickering 1918), as the violet opacity which is a typical carbon star feature only appears in the N stars. Classification of the N stars based on the increasing weakness in the relative intensity of violet light (Cannon & Pickering 1918; Shane 1928) is only useful for the nearer carbon stars, as few N-type carbon stars are bright enough to be readily observable in the blue or violet. Keenan & Morgan (1941) attempted to extend the MK system to the N stars by using the red region of the spectrum, with the intensity of the Na D lines as the main temperature indicator. However, this was shown by Scalo (1973a) to be influenced by the opacity, such that a low C/O ratio leads to low opacity from CN and hence a high electron pressure at given optical depth, so that there is an unusually high proportion of neutral Li, Na, K and Rb compared to other carbon stars. This results in strong Na I D lines in carbon stars with low C/O. An obvious feature of the red spectral region is that there is not a great range in the appearance of the spectra among optically-selected N stars, in contrast to the situation for the M stars (Lançon & Wood 2000). A luminosity classification is always likely to be problematic, given that these are giant stars of a limited range in luminosity and that the features used in estimating luminosities of ordinary giant stars are just those whose abundance excesses define the carbon stars. Eglitis *et al.* (2003) proposed a one dimensional spectral typing based on the intensity ratios of CN bands, using the ratios of CN (4, 0) at 620.6 nm to CN (5, 1) at 633.2 nm and also CN (6, 2) at 647.8 nm to CN (7, 3) at 663.1 nm.

A third major group of carbon stars is sometimes distinguished; the J stars, which have relatively strong ^{13}CN at 626.0 nm compared to ^{12}CN at 620.6 nm (Bouigue 1954). Gordon (1971) defined the group by an enhanced ^{12}C^{13}C band at 616.8 nm relative to ^{12}C^{12}C at 612.2 nm. The J notation is not quantitative and fails in stars in which the relevant bands are weak, whether because the star is too hot to show strong bands, as in R stars of type earlier than about R3, or because C/O is relatively small. The large survey of the LMC by Morgan *et al.* (2003a) and the surveys of galactic stars by Yamashita (1972, 1975), Dean (1976) and Lloyd Evans (unpublished) agree in placing the incidence of J stars among the N-type carbon stars as between 10 and 20%.

The difficulties with classical spectral classification have inspired several attempts to combine spectroscopic and photometric data in order to distinguish better between different groups of carbon stars. Lloyd Evans (1986a) used *BVRIJHK* photometry with spectroscopic classifications of galactic R stars and found a bifurcation in the two colour diagrams such that the J stars, most of which are classified as R5 in the Henry Draper catalogue, have bluer $(B–V)$ than CH stars of similar $(V–I)$ or $(J–K)$. This difference between the spectral energy distributions (SEDs) of CH stars and the J stars, which belong to populations of different average metal content but which both have enhanced ^{13}C (Vanture 1992a), may result from depression of the V band by the systematically stronger molecular bands in the J stars. The HdC stars also stand apart in the two colour diagrams: their SEDs differ from those of CH and R stars, probably because the H-deficient atmosphere lacks the H^- opacity which dominates in stars of normal H abundance.

Green *et al.* (1992) found that the dwarf carbon stars are redder in $(H–K)$ at a given $(J–H)$ than other warm carbon stars. This trend is similar to that shown by the high velocity giants such as V Ari and the Magellanic Cloud carbon stars (Cohen *et al.* 1981), though the latter are mostly N stars and are redder overall; they also share the combination of weak CN and strong C_2 (Lloyd Evans 1980b).

De Mello *et al.* (2009) devised a scheme which combines elements of the purely spectroscopic schemes, following that used by Hatzidimitriou *et al.* (2003) for LMC stars, with a temperature index obtained by modelling the SED from 500 nm to 100 μm to obtain the effective temperature of the central star. Other indices represent the strengths of the C_2 bands and the Merrill-Sanford bands of SiC_2, the $^{12}C/^{13}C$ ratio, the optical depth of the circumstellar material and the spectral features near 10 μm. The temperature index defines wide intervals in temperature, which are chosen to match the earlier work of Yamashita (1972, 1975), Keenan (1993) and Barnbaum *et al.* (1996).

Photometry has been combined with measurements of angular diameter to calibrate colours as a function of effective temperature. Angular diameters were obtained from lunar occultations (Ridgway *et al.* 1981) or from interferometry (van Belle & Thompson 1999). Bergeat *et al.* (2001) list those determined up to 2000. Tsuji (1981) used the infrared flux method to obtain satisfactory agreement with the results available from angular diameters at that time. Bessell *et al.* (1983) used *JHK* photometry to provide an interpolation device in the temperature scale determined from angular diameters.

Loidl *et al.* (2001) discussed the suitability of several possible temperature-sensitive colour indices in the visible and near-infrared spectral regions, with the aid of model atmospheres. Tanaka *et al.* (2007) estimated effective temperatures for a sample of bright carbon stars from each of the main groups outlined by Keenan (1993). These temperatures were derived by fitting near-infrared spectra with model spectra, using wavelengths which are not affected by strong molecular bands. The $T_{\rm eff}$ values, which range from 5100 K at C–H1 to 2600 K at C–N5, are well correlated with the spectral types of Barnbaum *et al.* (1996), except those of the N stars which fall in the range 2600–3100 K without obvious correlation with the types C–N4 to C–N6. An even wider spread is apparent for the J stars, with a range of 2800–3900 K in $T_{\rm eff}$ for stars of types C–J4 to C–J5, but 3400 K at C–J3.5. $T_{\rm eff}$ values for the C–R stars range from a mean of 4900 K at C–R2 to 4200 K at C–R3 and 2800 K at C–R4, indicating some overlap with the C–J group. The C–H group has values of 5100 K at C–H1, 4400 K at C–H3 and 4100 K at C–H4.

Knapik & Bergeat (1997) obtained SEDs by collating photometry from many sources in the range from U to the *IRAS* 25 μm band. They selected a colour index, $([1.08] - K) - C_{IB}$, where $C_{IB} = [0.78] - [1.08]$, and [0.78] and [1.08] are narrow band pseudo-continuum points, where CN absorption is minimal, measured by Baumert (1972). This index has the valuable property of being almost perpendicular to the reddening line in the $([1.08] - K) - C_{IB}$, C_{IB} diagram. The range from about 0.5 to 1.2 is divided in six regions, CV1 to CV6: $(B–V)$ and $(J–K)$ increase monotonically from CV1 to CV6, while C_{IB} remains almost constant.

Any non-Mira, visually selected, carbon star can be assigned to one of these classes. Bergeat *et al.* (2001) used the angular diameters for 52 stars to show that these classes are well correlated with effective temperature and went on to derive effective temperatures for 390 carbon stars. The temperature is not well determined for CV1, but for the other groups the derived temperatures are CV2: 3130 K, CV3: 2940 K, CV4: 2790 K, CV5: 2720 K, CV6: 2385 K and CV7: 1925 K. The CV groups thus provide a satisfactory interpolation. The mean C/O ratio increases from 1.04 to 1.36 as the temperature decreases. Bergeat *et al.* (2002) used these temperatures to plot over 300 carbon stars in the $M_{\rm bol}$, $\log(T_{\rm eff})$ diagram.

The ranges in temperature and colour on the AGB have been explained by Marigo (2002) as a consequence of the increasing atmospheric opacity as C/O increases during the evolution of an AGB star. This causes cooling and explains the jump in colour at the change from an atmosphere with C/O $<$ 1 to C/O $>$ 1. This also explains the relative blueness of the carbon stars with the least excess of C over O but which have exceptionally strong Na D lines, because the electron pressure is high (Scalo 1973a), leading to a late type as classified on the MK system (Keenan & Morgan 1941). These stars are not the coolest but are among the hottest of the N stars. The long tail in the infrared colour distribution of the carbon stars, as is seen in the Magellanic Clouds (Nikolaev & Weinberg 2000), is also accounted for (Marigo *et al.* 2003).

The TP-AGB models incorporating the new atmosphere models were combined with evolutionary tracks for previous evolutionary phases to obtain theoretical isochrones for a wide range of age and metallicity, which were compared with observational data for the Galaxy and the Magellanic Clouds. The run of colours of intermediate-age clusters in the Magellanic Clouds is well reproduced (Marigo *et al.* 2008). Synthetic photometry for dust-free hydrostatic models (Aringer *et al.* 2009) yield $(J–H)$ and $(J–K)$ colours which peak near 1.1 and 1.5, respectively, much less than the values found for many carbon stars. These decrease as the stellar temperature is reduced further and absorption by polyatomic molecules in H and K strengthens, but allowance for absorption by circumstellar dust and for the effects of pulsation and mass loss on the density structure of the atmosphere will result in improved agreement with observation.

4. Extrinsic carbon stars

The CH stars were recognised from the start (Keenan 1942) as high velocity stars and members of the galactic halo. McClure & Wordsworth (1990) found binary orbits for eight in a sample of ten CH stars, as well as 16 of 22 Ba II stars, the putative equivalent in the old disk population. Some of the remainder have orbits of long period, which have yet to be determined. McClure (1997) found orbits for two additional examples. The mass functions, with reasonable assumptions as to the mass of the primary, suggest that for both Ba II and CH stars, the unseen secondaries have masses near 0.6 $M_\odot$.

It seems plausible that these would be white dwarfs. The giant stars are too faint for the third dredge-up on the upper AGB to be responsible for the enhanced carbon and s-process abundances; it is now widely accepted that these enhancements result, not from interior processing, but from the acquisition of processed material from the companion when, as the more massive star, it passed through the AGB stage and transferred material to the companion. The former secondary, now seen as a giant star with modified composition, is therefore an extrinsic carbon star.

Bell & Dickens (1974) found enhanced ^{13}C on low resolution spectra of the two brightest CH stars in Omega Cen. Vanture (1992a) observed hotter field CH stars at high resolution and found six CH stars with $^{12}C/^{13}C$ in the range 3–8 and two with values of at least 25. Kipper & Jørgensen (1994) and Aoki & Tsuji (1997) added another three stars, all with low values. This is still a small sample, but the predominance of small values of $^{12}C/^{13}C$ is striking. The J stars account for only about 15% of all cool carbon stars in the Galaxy, so it is unlikely that they would account for most of the carbon donating original primaries. None would be plausible donors if all J stars are single, as McClure (1997) found for his sample of R stars which included many ^{13}C-rich stars classed as R5. Vanture (1992b) found that stars with high $^{12}C/^{13}C$ ratios also have higher C/N ratios than those with low ratios, which suggests that ^{12}C-rich material has been accreted and then subjected to CN burning in the CH star itself, in the case of the stars with low $^{12}C^{13}C$ and low C/N. Vanture (1992c) found that the heavy s-process elements were more enhanced than light s-process elements, with an average heavy to light ratio of 0.9 dex. He concluded that the abundance patterns were best explained if the neutrons came from the $^{13}C(\alpha,\ n)^{16}O$ reaction and seed nuclei were exposed to a single neutron irradiation. Later work at higher resolution yielded significantly different abundances for some of the s-process elements (Van Eck *et al.* 2003; Goswami & Aoki 2010). Van Eck *et al.* (2001) reported very high relative abundances of Pb in some CH stars; this was not found in the high velocity N star, V Ari (Van Eck *et al.* 2003).

The metal deficiency of the first dwarf carbon star (dC), G77-61, is remarkable, −5.6 dex (Gass *et al.* 1988), later revised to −4.0 (Plez & Cohen 2005). Dearborn *et al.* (1986) found that G77-61 is a single lined binary, of period 245 d, and the unseen companion is assumed to be a white dwarf. Subsequently white dwarf companions to several dwarf carbon stars were found (Liebert *et al.* 1994; Green & Margon 1994) and it seemed possible to consider these stars as an extension of the CH stars to lower luminosity.

Carbon stars of very low metallicity have been found at high galactic latitude by Christlieb *et al.* (2001) and by Beers *et al.* (1992). The proportion of C-rich stars increases to lower metallicity (Frebel *et al.* 2006). Cohen *et al.* (2006) found low values of $^{12}C/^{13}C$ for almost all of a sample of 16 stars, while 12 had strong enrichments of heavy nuclei (now known as CEMP-s) and four did not (CEMP-no). They suggested that the first group was binaries, as for the CH stars of the solar vicinity, while those of the second group were similar to R stars. Preston & Sneden (2001) found orbits for three of four CH giants found by Beers *et al.* (1992), while Lucatello *et al.* (2005) suggest that all of a sample of the CEMP-s group may be binaries, which supports the suggestion that these stars owe their peculiar composition to binary interaction. Masseron *et al.* (2010) suggest that the CEMP-s stars with only s-process elements enhanced were polluted by low mass AGB stars via the ^{13}C neutron source, while CEMP-rs stars, with r-process elements also enhanced, owe their peculiarity to the

^{22}Ne neutron source. Bisterzo *et al.* (2010) have provided theoretical predictions of the abundances of many s-process elements produced in AGB stars of a range of masses, metallicities and ^{13}C-pocket efficiencies.

Venn & Lambert (2008) note that the abundances of the elements in three extremely metal deficient stars show a dependence on condensation temperature and resemble those of some post-AGB stars whose atmospheres have been depleted in heavy elements, possibly by dust-gas separation in a circumstellar disc. Observations to check for the possible presence of a dusty disc have yet to be made.

Jorissen & Mayor (1988) and Brown *et al.* (1990) found that those galactic field S stars which lack Tc, whose presence is a signature of recent s-processing, are all members of binary systems. Thus they too owe their peculiarity of composition to the same extrinsic process of transfer of material from a companion which is now a white dwarf.

5. Kinematics and galactic distribution

Dean (1976) analysed his own and published data to make kinematic solutions for carbon stars. The non-Mira stars of N type were found to be kinematically similar to F5 dwarf stars. This is what would be expected from current knowledge of the masses of carbon stars in the intermediate age clusters of the Magellanic Clouds. The scale height for the N-type stars, of all variability types, is close to 200 pc, which again suggests F type progenitors (Claussen *et al.* 1987; Groenewegen *et al.* 1992; Kerschbaum & Hron 1992).

Bothun *et al.* (1991) observed carbon stars at high galactic latitude; these have relatively large velocity dispersion of 96 km s^{-1}. This is a rather inhomogeneous sample, ranging from stars in the colour range of CH and R stars to stars which are heavily reddened by circumstellar dust. Mauron *et al.* (2007) used the red $(J{-}K)$ of cool carbon stars to find distant N stars at high galactic latitudes. Substantial numbers of faint carbon stars have been found at high latitudes by the Sloan Digital Sky Survey (Margon *et al.* 2002; Downes *et al.* 2004). Proper motions show that up to 60% are dwarf carbon stars. The spectra are quite similar to those of giant stars, making discrimination difficult. The colours of the dwarf carbon stars and a new group, the F/G dwarfs which are hotter, are surprisingly scattered, especially in $(H{-}K)$.

A small number of nearby carbon stars, such as V Ari and TT CVn, have very high velocities. These stars have spectra characterised by strong C_2 and weak CN, while the isotopic bands are very weak and the metal content is very low but the s-process elements are over-abundant (Kipper & Kipper 1990; Tsuji *et al.* 1991; Kipper 1992; Aoki & Tsuji 1997). Their colours differ systematically from those of typical R and N stars and are similar to those of the Magellanic Cloud carbon stars (Lloyd Evans 1980b, 1986a and in preparation; Cohen *et al.* 1981; Suntzeff *et al.* 1993; Ulla *et al.* 1997). These Magellanic Cloud carbon stars are known to be of intermediate age, so the existence of similar stars with velocities typical of the very old halo stars of the Galaxy presents a problem. It is possible that they are stars which were acquired by the Galaxy in the cannibalisation of a smaller galaxy.

The C:M ratio is greater the lower the metal content of a stellar system. This results from two factors. The abundances of both Ti and O are reduced, so the TiO bands are weaker and consequently the M stars are fewer and of earlier M subtype. Also, the reduced O abundance means that less fresh C has to be dredged up from the He-burning interior to overturn the C/O ratio in the outer layers. For long, no carbon stars were found in the Central Bulge of the Galaxy (Blanco *et al.* 1978b), although M stars are present in profusion (Blanco *et al.* 1984). Carbon stars were however found by Azzopardi *et al.* (1991). Lloyd Evans (1985a) and Westerlund *et al.* (1991b) found that the brightest of these are J stars and are relatively blue and hot; some might be CH stars. Neither would be formed by the third dredge-up on the thermally pulsing AGB, so the earlier conclusion is unaffected.

Demers & Battinelli (2007) obtained radial velocities of carbon stars at large galactocentric distances to obtain results suggesting a flat rotation curve to a distance of 15 kpc. Two deviant stars may belong to the Canis Major overdensity.

6. Variable stars

6.1 *Long period variables*

Carbon stars are known in all the main classes of variable which are found in the parts of the H–R diagram in which carbon stars are found, and in addition, have one class peculiar to themselves, the R Coronae Borealis stars, which are Hydrogen-deficient carbon stars. Red variables appear high on the red giant branch of globular clusters; in the Magellanic Clouds it has been possible to distinguish separate Period-Luminosity (P–L) relations for RGB and AGB stars as well as for stars pulsating in the fundamental mode (Mira variables) and in higher radial modes as semiregular variables (Wood *et al.* 1999; Cioni *et al.* 2001, 2003; Lebzelter *et al.* 2002; Kiss & Bedding 2003, 2004; Groenewegen 2004; Ita *et al.* 2004; Fraser *et al.* 2008; Soszyński *et al.* 2009). The same pattern has been found for the red variables in the intermediate age clusters NGC 1846, which has 22 variables of types M, S and C (Lebzelter & Wood 2007), NGC 1978 with 13 variables and NGC 419 with 20 variables (Kamath *et al.* 2010). Stars of spectral type M are found below the tip of the Red Giant Branch (RGB) but carbon stars, defined as having $(J - K_s) > 1.4$ in the absence of spectroscopic data, are only found above this point, which corresponds to K_s of 12.1 in the LMC and 12.7 in the SMC (Kiss & Bedding 2003, 2004; Ita *et al.* 2004). Cioni *et al.* (2001) and Groenewegen (2004), who cross-correlated the photometry with spectroscopically-determined spectral types, found that the carbon Miras appear about 0.7 mag in K above the tip of the RGB.

The carbon Miras in the LMC follow almost the same P–L relation as the M type stars (Groenewegen & Whitelock 1996; Groenewegen 2004). Carbon Miras offer one of the best means available for distance determinations in small galaxies with a large intermediate age population and where a low metal content means that the Mira variables are mainly carbon stars, as in the case of the SMC (Lloyd Evans *et al.* 1988; Groenewegen 2004). Kiss & Bedding (2004) warn that there is a fairly dense scattering of heavily reddened Mira variables below the main P–L sequence (Wood 1998), so care needs to be taken to avoid using reddened stars in deriving the distance modulus. Nishida *et al.* (2000) obtained near-infrared photometry of three obscured carbon stars in Magellanic Cloud clusters and found that they lay on the extended P–L relation when bolometric magnitudes were used but up to 0.7 mag faint at K, showing the influence of circumstellar extinction.

Variable stars in the galactic field are not easily separated into the various pulsation groups as their distances are not known. The well known distinction between Mira and semi-regular variables at an amplitude of 2.5 mag is only applicable to M stars and then only strictly for those of a limited range of spectral type: the relatively large visual amplitudes of M type Miras result from variations in TiO band strengths, which are at their strongest in the region near 500–600 nm. The TiO bands are relatively weak near maximum light, when the star is hottest, but as it expands and cools, TiO forms throughout the atmosphere and the effective photospheric diameter increases by a factor of about 1.8 while $T_{\rm eff}$ falls to around 2000 K, so the star radiates mainly in the infrared and fades in visible light (Reid & Goldston 2002). Lançon & Wood (2000) find that for carbon stars, in contrast, there is little change in the spectrum over a wide range in wavelength, because whereas the important molecules TiO and H_2O in M stars are formed at temperatures from 3500 K to as little as 2000 K and so are found in the upper atmosphere where they are affected by shocks and other dynamic events, CO, CN and C_2 are formed at temperatures of 3000–5000 K, deeper in the atmosphere where they are less affected by dynamics (Loidl *et al.* 2001). This also explains why, whereas M type Miras have variable V magnitudes at maximum and minimum light, those of carbon Miras generally do not change much from one cycle to the next (Lloyd Evans 1997).

The visual amplitudes of carbon Miras are consequently less than those of M-type Miras, so they are often classified as semi-regulars. Whitelock *et al.* (2003) show, however, that the amplitudes at 2.2 μm are as large in carbon as in M-type Miras in the LMC, and probably even larger for the stars of longest period, many of which are obscured visually by circumstellar dust. Cioni *et al.* (2001) find that semiregular M and C stars in the LMC have similar amplitudes in the R band, whereas semi-regular carbon stars in the SMC have larger amplitudes in both R and B (Cioni *et al.* 2003).

6.2 *R Coronae borealis variables*

Stars of the R Coronae Borealis (RCB) type are found only among H-deficient carbon stars (HdC), though they range widely in the degree of H-deficiency. Their characteristic feature is the occasional occurrence of drops in brightness of up to 9 magnitudes, with a rapid drop and a usually slower recovery which may extend over several years. Clayton (1996) lists 37 probable members of the group, including three in the LMC and three which are hot extreme helium stars which would not appear in lists of carbon stars. A few new examples have since been recognised in the general field in the Galaxy (Clayton *et al.* 2002, 2009; Hesselbach *et al.* 2003), while the extensive variable star surveys of recent years have detected 14 in the Galactic Bulge (Zaniewski *et al.* 2005; Tisserand *et al.* 2008). There are now at least 25 known in the LMC (Alcock *et al.* 1996, 2001; Morgan *et al.* 2003b; Tisserand *et al.* 2009) and two or three, yet to be confirmed, in the SMC (Kraemer *et al.* 2005; Tisserand *et al.* 2009). Their absolute V magnitudes at maximum light range from -2.6 to -5.2 in the Magellanic Clouds (Tisserand *et al.* 2009).

Loreta (1935) and O'Keefe (1939) put forward the accepted explanation for the fading events, that the star ejects clouds of carbon dust which obstruct the light of the star until they dissipate. Frequent photometric and spectroscopic observations of fading events of R CrB (Payne-Gaposchkin 1963) and RY Sgr (Alexander *et al.* 1972) revealed the appearance of a chromospheric-type emission spectrum early in the decline and a few broad emission lines later on. Payne-Gaposchkin (1963) suggested that the dust formed in the photospheric region below the chromosphere and obscured the normal photospheric light. The chromospheric spectrum disappeared in its turn as the star faded further while the dust cloud rose higher; displaced absorption lines indicate a terminal velocity of 200 km s^{-1} for the ejected material. The observation that the onset of decline is related to the phase of radial pulsation of the star (Lawson & Crause 2007) and calculations on the rate of fading (Clayton *et al.* 1992) both suggest that a cloud formed close to the photosphere. Feast *et al.* (1997) found evidence for the ejection of dust in a puff of small angular extent as seen from the star, rather than in a larger or more regular form, in the lack of correlation in variations at J and L, as L arises from the emission from a dust cloud comprising material ejected in many individual events and will not be affected by the cut-off of emission from only a small part of the stellar surface. The dust formation was suggested (Feast 1997) to occur at about $2R_*$, possibly above a convective cell as suggested by Wdowiak (1975). Kawabata *et al.* (2007) reported relatively large polarisation of R CrB at maximum light, suggesting the existence of short lived puffs ejected away from the line of sight, and deduced from their transience that they must lie within $2R_*$ of the photosphere. The detection of CO in the spectra of RCB stars supports the idea that grain formation in the hot region near the photosphere might follow shock induced cooling followed by a sharp increase in the CO column density and subsequent severe cooling by radiation in the infrared bands (Clayton *et al.* 1999a, 2007).

Imaging of UW Cen shows major changes in the morphology of a surrounding nebula in only 8 years (Clayton *et al.* 1999b). The radius is estimated as 6×10^{17} cm, so the changes cannot result from the physical motion of gas ejected at 200 km s^{-1} but may be understood as representing the varying illumination of the outlying circumstellar material by starlight reaching it through gaps between discrete clouds nearer the star. Interferometric observations confirm the presence of a discrete dusty cloud at about 100 R_* from the centre of RY Sgr (Leão *et al.* 2007).

There is uncertainty over the nature of a subgroup of the RCB stars, typified by DY Per (Alksnis 1994). These are cooler than most recognised RCB stars and lack the pronounced underabundance of hydrogen. DY Per, the best studied of the group, has fairly regular minima of depth about 2 mag in a period of 792 d and minima of up to 5 mag which are more erratic but which keep approximately to the 792 d cycle (Alksnis *et al.* 2002). The type star is at most moderately H-deficient (Keenan & Barnbaum 1997; Začs *et al.* 2007), while s-process elements are not enhanced. $^{12}C/^{13}C$ is similar to the values found in typical N stars (Začs *et al.* 2005, 2007), in contrast to the absence of ^{13}C in the spectra of most RCB stars. Absorption components of Na I D are attributed to two separate clouds of ejected material with velocities up to 170 km s^{-1} (Keenan & Barnbaum 1997; Začs *et al.* 2005). There is possible emission of C_2 in deep minima (Začs *et al.* 2007).

Observations of DY Per stars in the Magellanic Clouds confirm the moderate $^{12}C/^{13}C$ ratios (Alcock *et al.* 2001; Morgan *et al.* 2003b; Tisserand *et al.* 2009). The spectral energy distributions, determined over the range of wavebands from B to the 24 μm band of MIPS on *Spitzer*, are all very similar, with a single peak near 1.6 μm, in contrast to the frequently double-peaked SEDs of the RCB variables. However, Alksnis *et al.* (2009) were able to represent the energy distribution of DY Per in *BVRIJHKLM* by the sum of two black body distributions. The DY Per stars fall in the region of the near infrared two-colour diagrams occupied by the ordinary carbon stars, without overlaping with the RCB stars, in accordance with the lack of substantial H deficiency. This leads to the suggestion that the DY Per stars are ordinary carbon stars with ejection events (Tisserand *et al.* 2009). Judgment on this point should perhaps be suspended until more stars have been studied in detail: the high velocity clouds in DY Per are the only feature which seems out of place in an N star. Feast *et al.* (2003) suggested that RCB type ejection also accounts for the dust fading events which occur in N type Mira variables, on a much longer time scale than those of RCB and DY Per variables. Stars like DY Per are not Mira variables but the apparent periodicity of the fadings in DY Per is very suggestive, as the period is of the same order as some of those found in the semiregular variables with long secondary periods (LSP) in the Magellanic Clouds and elsewhere. Wood & Nicholls (2009) have found that Magellanic Cloud stars with LSPs show a significant mid-IR excess compared to stars without LSPs. They suggest that LSPs cause ejection of material, probably in a clumpy configuration.

6.3 *Type II Cepheids*

Lloyd Evans (1983b) listed seven known or suspected carbon stars among the type II Cepheids. Three of these have published abundance analyses, which give very similar results including near solar Fe abundance, enhanced ^{13}C with $^{12}C/^{13}C$ of 4–5, no s-process enhancement and a low radial velocity which suggests membership of the galactic disc (V553 Cen, $P = 2.06$ d: Wallerstein & Gonzalez 1996; RT TrA, $P = 1.95$ d: Wallerstein *et al.* 2000; RU Cam, $P = 22.1$ d: Kipper & Klochkova 2007). RU Cam has a highly variable light amplitude (Demers & Fernie 1966; Kollath & Szeidl 1993). DI Car ($P = 29.2$ d) is also erratic (Laney, private communication) and is a J star, while RV Nor is a similar star of $P = 32.3$ d.

V1181 Sgr, also listed by Lloyd Evans (1983b), may instead be an RV Tauri variable of Preston spectroscopic class B, in which CN and sometimes C_2 are enhanced. These stars do not appear to be C-rich, but the strong bands may result from the relatively high content of the CNO group in an atmosphere depleted in most other elements (Giridhar *et al.* 2005). The RV Tauri star MACHO 47.2496.8 in the LMC (Alcock *et al.* 1998), which has the long double period of 112 d and is one of the brightest RV Tauri stars in the LMC, is a true carbon star (Pollard & Lloyd Evans 2000). It is metal deficient, with a large overabundance of s-process elements and a high value of $^{12}C/^{13}C = 200$. The bolometric luminosity places it on the lower limit of N stars in the LMC, so it seems likely to be a low mass star (Reyniers *et al.* 2007).

Some of the R Coronae Borealis stars lie in the Cepheid instability strip and pulsate, somewhat irregularly, with periods which are typically about 40 days. Alexander *et al.* (1972) and Lloyd Evans (1986b) present light curves of the pulsations of RY Sgr.

An observational feature of all these stars is that the bands of C_2 and CN which identify them as carbon stars are strongly dependent on temperature and at the mean temperature of the Cepheid instability strip, the bands are virtually invisible at maximum light and appear strongly only when the star is near minimum light in the pulsation cycle, so that detection as a carbon star depends on obtaining observations at the right phase. Lloyd Evans *et al.* (1972) give a plot of band strengths against phase for V553 Cen and Lloyd Evans (1986b) does the same for the RCB star RY Sgr.

7. Dust fadings and the outer atmospheres of N and J stars

Early spectroscopy revealed the extreme faintness of the cooler carbon stars at wavelengths shorter than about 450 nm (Shane 1928; Shajn & Struve 1947). Shajn & Struve (1947) found that the absorption lines in this region, notably the normally strong H and K lines of Ca II, appear extremely weak by comparison with those in M stars of similar effective temperature. This was attributed to an additional source of absorption in the atmospheres of N stars. McKellar (1948) noticed the probable presence of C_3 near 405.0 nm. Swings *et al.* (1953) studied the violet region as far as 350 nm and confirmed the presence of C_3 in Y CVn, U Hya and possibly in other stars. The appearance of the 405 nm bands of C_3 in U Hya were correlated with high opacity in the far violet and with the presence of the blue-green bands which were later identified as SiC_2 by Kleman (1956). Additional supposed absorption features were shown by Gilra (1976) to be the gaps between emission by low excitation lines of Ti I, Zr I and V I. Violet region spectroscopy by Lloyd Evans (unpublished), using a photon counting detector which permitted sky subtraction, confirms the presence of C_3 bands, as well as the atomic emission lines, in a few stars. The absorption bands of C_3 were found to be strong only in two J stars, T Mus and HD 148173, but are weakly present in several N stars, notably the Mira variable R Lep. Many other stars lack C_3 bands.

The source of the violet opacity has been a longstanding problem. Suggested mechanisms have included absorption by C_3 molecules or atomic lines or extinction by solid particles. Walker (1976) showed that there was a close correlation between the strength of the violet opacity, represented by the $(B–V)$ colour of a star, and that of the SiC_2 bands. This indicates the possibility that SiC grains, known from mid-infrared spectra (Olnon *et al.* 1986) to be present in the circumstellar material around many carbon stars, are the responsible agents. The increasing weakness and ultimate disappearance of atomic and molecular absorptions as stars with successively greater violet opacity are considered and it suggests that the dust must lie within the atmosphere and above the levels where these features are formed, so that the visible absorption lines are produced in a successively thinner layer.

The SiC_2 molecule is of considerable interest in connection with the outer layers of carbon star atmospheres, as laboratory studies (Michalopoulos *et al.* 1984) indicated that it has a triangular and not a linear structure as originally supposed. The Si atom is relatively weakly bonded to a C_2 entity, so vibrational hot bands exist with an excitation temperature of only 281 K. The hot bands are seen in absorption in the spectra of most cool carbon stars, where they may arise in the upper atmosphere with a lower temperature than that of the photosphere (Sarre *et al.* 2000). They are absent from the emission spectrum of IRAS 12311-3509, where the other bands of SiC_2 arise in cool circumstellar material (Lloyd Evans *et al.* 2000). The hot bands are normally present in the absorption spectrum of T Mus, a semi-regular variable with a long secondary period (LSP) of 1082 d (Lysaght 1989) and variable amplitude which is also a J star (Barnbaum *et al.* 1996), but they disappeared when it underwent a deep minimum in 1994 (Sarre *et al.* 1996). A deeper minimum in 1999 lead to the disappearance of almost all absorption lines as well and the appearance of strong emission at the C_2 bandheads, especially of the (1, 0) bandhead, where both the $^{12}C^{12}C$ head at 473.7 nm and the $^{12}C^{13}C$ head at 474.4 nm appeared, as well as the 471.5 nm (2, 1) bandhead where the isotopic head was also visible, while the (0, 0) head at 516.5 nm showed relatively weak emission. These relative intensities are clearly anomalous. The hot bands of SiC_2 disappeared, leaving the remaining bands of SiC_2 as the only strong absorption features in the spectral region to the blue of 520 nm. However, the red part of the spectrum was virtually unchanged (Lloyd Evans 2007). A tentative explanation is that dust was produced in the atmosphere above the levels at which most features, other than the remaining SiC_2 bands, are formed. The rapid increase of the dust absorption to the violet accounts for the much greater abnormality at shorter wavelengths. It is not clear how this phenomenon relates to the mass loss found to be associated with the semi-regular variables with LSPs (Wood & Nicholls 2009); it seems plausible that the fading of T Mus was associated with dust formation and possibly ejection, but there is no contemporaneous infrared photometry to confirm this.

This behaviour has similarities with that noted in the normal pulsations of carbon Miras: the C_2 band at 473.7 nm appears in emission at times and may be quite strong, whereas the (0, 0) band at 516.5 nm is little affected (Lloyd Evans 1989). Continued observations of several carbon Miras (Lloyd Evans unpublished) show that this emission varies strongly round the cycle: normal absorption is present at maximum light, while emission appears when the star is near minimum. Le Bertre (1988) interpreted broadband photometry of R For round the pulsation cycle with a radiative transfer model. The increased obscuration of the central star around minimum light is attributed to the formation of dust in the inner part of the circumstellar shell, as a consequence of the lower luminosity at minimum. The greater spectral abnormality at shorter wavelengths results from the increasing absorption by the dust. Mira variables differ considerably in the range of wavelengths over which the violet opacity is apparent. Some are less affected than stars such as R Lep and never show C_2 emission at 473.7 nm, while in others, such as the extreme carbon star II Lup (IRAS 15194-5115), heavy absorption means that little can be seen below 600 nm. It would be worth looking for emission in the (0, 0) bandhead at 516.5 nm or the (0, 1) head at 563.5 nm in a suitably red star.

A different spectroscopic development is observed during the dust fadings of carbon Miras (Lloyd Evans 1997; Smirnova *et al.* 2009), in which we may see individual minor episodes of mass loss. These fadings occur at intervals of decades with unknown, if any, periodicity in the redder of the well known bright carbon Miras, as revealed by AAVSO data. R Lep was followed through a deep minimum and found to show emission in the C_2 bands and in resonance lines of Na I, K I and Rb I. Spectroscopically similar fadings occur at regular intervals of 18–19 years in the SRa, LSP variable, V Hya, which has an unusual companion (Lloyd Evans 1991a). These spectral abnormalities do not show a dependence on wavelength. The emission in the C_2 bandheads is much stronger at the fundamental (0, 0) head at 516.5 nm than at the (1, 0) head at 473.7 nm and the emission of resonance lines in the yellow to far red spectral regions are strong, suggesting that in this case the dust lies above the region where the emission features are formed. Feast *et al.* (2003) suggested that the emission features arose in the outer atmosphere and became visible when the photospheric disc, but not the surrounding region, was dimmed by the dust cloud. Le Bertre (1988) discussed the deep minimum of R For in 1983, reported by Feast *et al.* (1984), and suggested obscuration by dust which condensed in the inner part of an existing circumstellar shell, as a result of the reduced luminosity of the star at minimum. He did not find it necessary to postulate ejection of a shell or eclipse by a dust cloud. There is no contemporary spectroscopy of this event, much shorter than those of R Lep and V Hya, to compare with the other stars which have undergone dust fadings. Lloyd Evans (1997) noted that the three stars for which *JHKL* photometry through a fading was available, R For, R Lep and V Hya, all followed the general trend of carbon stars in the two colour diagrams, without the infrared excess shown by RCB stars. This is a less sensitive test for asymmetric dust clouds than it is in the RCB stars, as there is less contrast between the emission from hot dust and from the photospheres of such cool stars.

Whitelock *et al.* (1997) rediscussed the situation, with data for fadings of other stars as well. They suggested the faintness of R Lep, from the trigonometric parallax obtained by Hipparcos, relative to the luminosity from the P–L relation indicated an asymmetrical cloud such as the RCB stars eject. Feast *et al.* (2003) presented data for a protracted fading of II Lup (IRAS 15194-5115): there was a much smaller range in L than in J, and contemporaneous infrared speckle observations by Lopez *et al.* (1993) indicate that at deep minimum almost all the flux at J came from the photosphere and almost all that at L came from the dust. The combination of a constant dust shell with variable dust opacity in the line of sight requires an asymmetric model.

Feast *et al.* (2003) suggested that the dust formation took place above the cool regions of large convective cells, as may be the case in RCB stars. Possible support for this suggestion comes from the anomalous spectra of V Hya some months before the start of the 1993 decline (Lloyd Evans 1997). The normal heavily obscured spectrum, accompanied by emission and near absence of absorption in the 473.7 nm (1, 0) bandhead of C_2, was replaced by the much bluer spectrum typical of a hotter carbon star, with strong absorption at the (1, 0) bandhead, in February and April 1992. There was no perceptible increase in the brightness at V, but V Hya is so red that brightness changes in the 480 nm region have relatively little effect on V, whereas even if a limited region of the surface were freed of the violet opacity it could transform the appearance of the spectrum at shorter wavelengths. This might indicate the arrival of a hot convective element at the surface. Johnson's (1993) observation of a major increase in the polarisation of V Hya early in the fading episode of 1993 suggests a highly asymmetric situation, which would, *inter alia*, be consistent with the ejection of a dust cloud at an angle to the line of sight, or to the intrusion of a dust cloud around the secondary star at inferior conjunction in this binary system, as in the case of Epsilon Aurigae.

The SC star UY Cen is the only other carbon star that have been observed spectroscopically during a dust fading event, which occurred in 2002 (Steinfadt *et al.* 2005). No unusual spectroscopic features were seen, although the depth of minimum, 2.5 mag, was comparable to that of the other stars discussed here. However, if the fading of UY Cen, which is classed as a semi-regular variable with a period of 114.6 d and amplitudes in V and in the blue of 0.6 and 1.7 mag, respectively, was similar to that of T Mus this would have escaped notice, as the spectrum was observed only in the red in 2002. ASAS (Pojmanski 2002) and AAVSO data show a slow and erratic brightening after the deep minimum in early 2002, with maximum brightness reached only in 2008, and a subsequent slow decline. It is of some importance if this fading was caused by dust, as elsewhere we note arguments that SC stars do not readily produce dust.

It can be concluded that only three stars have been observed spectroscopically through a dust fading event, and it appears that there are two different types of event: that seen in T Mus (Lloyd Evans 2007) and those in R Lep and V Hya (Lloyd Evans 1997). It must be kept in mind that R Lep and V Hya are very different stars in that R Lep is a Mira with major fadings perhaps a half century apart while V Hya is a Mira or SRa which is also a star with an LSP of 19 years. It has a companion and suffers bipolar mass loss (Sahai & Wannier 1988; Tsuji *et al.* 1988). More observations are required, including spectro-polarimetry and interferometry.

8. Mass loss

Typical outflow velocities for the circumstellar material, represented by CO, relative to optical photospheric velocities, are 10–20 km s^{-1} (Olofsson *et al.* 1987, 1988). The outflow velocities show a dependence on $^{12}C/^{13}C$ and are typically only 5–10 km s^{-1} for J stars. Stars with dense dusty shells, indicated by redder (J–K) colours, have larger outflow velocities, up to 40 km s^{-1} and averaging about 20 km s^{-1}, but similarly red carbon stars in the halo and so presumably of low [Fe/H], have an average outflow velocity of only about 10 km s^{-1} (Lagadec *et al.* 2010). S stars have outflow velocities of typically 7.5 km s^{-1}, similar to those of M stars (Ramstedt *et al.* 2006). Outflow velocities from absorption in the resonance lines of K I in Mira variables are in good agreement with those deduced from CO emission in the same stars (Barnbaum 1992a, 1992b; Barnbaum & Morris 1992). Much higher velocities are seen in some stars, notably in the bipolar outflow from V Hya where velocities up to 220 km s^{-1} are found (Kahane *et al.* 1988, 1996; Tsuji *et al.* 1988; Sahai & Wannier 1988; Lloyd Evans 1991a; Knapp *et al.* 1997; Sahai *et al.* 2003, 2009). One of the expanding shells around another binary system, UV Aur, has a velocity of 116 km s^{-1} (Herbig 2009).

8.1 *Detached shells*

One type of circumstellar cloud which has been studied in detail is the detached shell: the literature published up to 1997 is discussed by Wallerstein & Knapp (1998). These geometrically thin spherical shells have been studied in eight stars to date and are characterised by far-infrared, typically 60 μm emission, but a lack of near-infrared emission as there is no hot dust near the star, and a ring-like morphology in maps of dust or CO line emission. Schröder *et al.* (1998, 1999) and Wachter *et al.* (2002) were able to account for the occurrence of this phenomenon around carbon stars, but not M stars, with theoretical models which indicate that only the carbon stars have a sufficiently high luminosity during the low mass loss rate stage of evolution to drive an intense mass ejection during a He-shell flash. Lindqvist *et al.* (1999) showed that the shell of one such star, U Cam, is geometrically thin, 10^{16} cm thick at 6×10^{16} cm from the star. The expansion velocity is 23 km s^{-1} and the mass is estimated to be 10^{-3} $M_\odot$. Emission at the stellar position indicates a present mass loss rate of only 2.5×10^{-7} $M_\odot$ yr^{-1}, with an outflow velocity of 12 km s^{-1}. Production of the shell in a 150 yr episode of high mass loss which occurred 800 yr ago, perhaps as the result of a He-shell flash, was suggested. Olofsson *et al.* (2000) observed a similar star, TT Cyg, which has an even thinner shell thickness of 1.9×10^{16} cm at 2.7×10^{17} cm from the star, and note an alternative mode of formation of the shell, in which a more modest mass ejection swept up material from a previous slower stellar wind. The shell of S Sct is relatively thinner still, only 0.20×10^{17} cm at a distance of 5.2×10^{17} cm (Yamamura *et al.* 1993). Schöier *et al.* (2005) performed radiative transfer modelling of both CO line emission and dust continuum radiation for seven of these objects and found signs of interaction with a surrounding medium. The estimated shell masses increase and their expansion velocities decrease with distance from the star. An interacting wind model indicates that the mass loss rate producing the faster moving wind has to be almost 100 times higher (10^{-5} $M_\odot$ yr^{-1}) than the slower moving AGB wind (a few 10^{-7} $M_\odot$ yr^{-1}). R Scl was noted as a somewhat different object to the rest: it is also the only one with regular pulsations of relatively large amplitude.

IRAS and *ISO* data were used to detect detached dust shells around several stars, not all among those for which thin shells have been studied using molecular lines. Izumiura *et al.* (1997) found that U Ant had an outer dust shell, at a radius of about 3 arcmin, while an inner dust shell apparently coincided with the thin shell observed in molecular lines. These shells might result from successive thermal pulses during AGB evolution. HST imaging of the shells of U Cam and R Scl in starlight scattered from the dust confirms that the dust and gas shells coincide spatially, while clumps of dust are seen in the shell of R Scl. These may result from instabilities in the expanding shell (Olofsson *et al.* 2010). Kerschbaum *et al.* (2010) imaged three stars with *Herschel*-PACS, one of which, AQ And, was selected because of the indication of very cool dust in the SED although it has no detected CO. Dust shells of TT Cyg and U Ant coincided with the molecular shells, at a radius of 42 arcsec in the case of U Ant, although the dust shells are thicker. However, Maercker *et al.* (2010) confirmed an earlier study by González Delgado *et al.* (2003) and concluded from polarisation data of the scattered starlight around U Ant that an inner shell, of radius 43 arcsec and thickness 2 arcsec, consists mainly of gas, whereas an outer shell, at 50 arcsec and 7 arcsec thick, is pure dust. Kerschbaum *et al.* (2010) saw no shell at 50 arcsec and noted that the absence of a shift between the dust and gas envelopes, which might be expected on the thermal pulse model, suggests an alternative wind–wind or wind–ISM interaction, as considered by Wareing *et al.* (2006). The circular shell would only be expected if the star's motion were in the line of sight in the case of a wind–ISM shock; a parabolic arc would result otherwise, as is seen for R Hya.

These detached shells are not exclusive to N-type carbon stars, as the J star Y CVn also has one (Libert *et al.* 2007). These authors prefer a model in which mass loss has been constant at $1.0 \times 10^{-7}\, M_\odot\, yr^{-1}$ for about 4.5×10^5 yr, as determined from H I observations. The initial velocity of the outflow is 8 km s^{-1} and the detached shell is caused by surrounding matter, which slows the expansion to 2 km s^{-1}. The sharp inner radius of the shell corresponds to the termination shock and the outer radius to the bow shock.

8.2 *Mass loss rates*

The AGB phase is terminated by the ejection of large quantities of matter, comprising much of the stellar envelope. Study of the later stages is greatly hampered by the dust component of the ejected material, so that infrared and radio techniques are the main sources of information. M stars are observed especially in the OH radio lines and large numbers of OH–IR stars have been observed. Carbon stars are even more heavily reddened by circumstellar dust: as Wallerstein & Knapp (1998) remark, carbon dust is opaque at visible wavelengths but silicate dust is not. Hence a large proportion of carbon stars are optically invisible: most were first detected by the *IRAS*-LRS instrument, on the strength of the SiC emission band at 11.2 μm.

Groenewegen *et al.* (1998) fitted a radiative transfer model to the SEDs and mid-infrared spectra of 44 carbon Miras. Mass loss rates, in the range $1 \times 10^{-8}\, M_\odot\, yr^{-1}$ to $4 \times 10^{-5}\, M_\odot\, yr^{-1}$, were found to be correlated with luminosity and pulsation period. Groenewegen *et al.* (2002) obtained millimetre observations of CO, HCN and SiO for a large sample of IRAS selected infrared carbon stars. Bolometric magnitudes, dust and gas mass loss rates, gas-to-dust ratio and expansion velocities were determined.

Known pulsation periods for some of the stars were used to determine bolometric magnitudes and to calibrate a relation between bolometric magnitude and the flux ratio in two *IRAS* bands: the more luminous stars are redder, as they have higher mass loss rates. This enabled distances and galactic distribution to be calculated. The expansion velocity was 18.7 km s^{-1} on average, with a significant dependence on galactic longitude. The expansion velocity, as well as the other derived quantities, was less outside the solar circle, as expected from the decline in metal content with distance from the galactic centre. Busso *et al.* (2007) obtained mid-infrared photometry for M, S and C stars. Carbon Miras showed higher mass loss than semi-regular variables. The carbon stars were more reddened than the M and S stars, but the amount of reddening was hard to estimate because the intrinsic photospheric colours were uncertain, a reflection of the lack of suitable molecular opacities to enter in model atmospheres (Marigo 2002). The mid-IR luminosity of most of the stars changed little in 20 years, the exceptions being stars with maximum emission at 8–20 μm. Whitelock *et al.* (2006) obtained infrared photometry for over 200 carbon-rich variable stars in the Galaxy and used the Mira P–L relation to obtain distances and luminosities. Mid-infrared photometry was used to derive mass loss rates of 10^{-7} to 10^{-4} $M_\odot$ yr^{-1}. Guandalini *et al.* (2006) collected data for a large sample of carbon stars and used astrometric distances, which are available for a subset, to obtain mass loss rates in the same range. The rates for semi-regular and irregular variables are smaller on average than those of Miras and generally fall in the lower half of the logarithmic range.

Groenewegen (2006) performed radiative transfer calculations for circumstellar envelopes with several dust compositions and a range of temperatures for M and C stars and hence obtained fluxes in the *VIJHK* bands as well as for those used in the *Spitzer* and *AKARI* infrared satellites. These have been used by Jackson *et al.* (2007a, 2007b) to estimate mass loss rates from stars in two dwarf irregular galaxies; these were mainly in the range 10^{-5} to 10^{-7} $M_\odot$ yr^{-1} in WLM but a factor of two less in IC 1613. A considerable fraction of the total current mass loss in each galaxy is contributed by a small number of stars with very high rates of mass loss.

Matsuura *et al.* (2007) observed five carbon AGB stars, including the three reddest, in the Fornax dSph galaxy, using the *Spitzer* infrared spectrometer. The three reddest stars have mass loss rates of only (4–7) $\times$ 10^{-6} $M_\odot$ yr^{-1} and the total mass loss from all the known carbon stars in Fornax is much less than in the WLM dwarf irregular, which has a younger stellar population. Lagadec *et al.* (2008) used *K* and 9 and 11 μm photometry of carbon and presumed carbon stars in the Fornax and Sagittarius dSph galaxies to estimate the rate of mass loss in the form of dust. Both calibrated colour-mass loss relations and radiative transfer models were used. The results are in the range 5×10^{-10} to 3×10^{-8} $M_\odot$ yr^{-1} of dust for stars in Sagittarius and about 5×10^{-9} $M_\odot$ yr^{-1} for stars in Fornax. The mass loss rates are higher than the nuclear burning rates, so these stars will deplete their mantles and leave the AGB before their cores will grow significantly.

Srinivasan *et al.* (2009) made a comprehensive study of mass loss from evolved stars of all types in the Large Magellanic Cloud. Groenewegen *et al.* (2009) used *Spitzer* infrared spectra, together with optical and infrared photometry, to construct spectral energy distributions (SEDs) for 101 carbon stars in the Magellanic Clouds. Dust radiative transfer models permit luminosities and dust mass loss rates to be estimated. The choice of dust types was constrained by the observations. The bolometric magnitudes of the carbon stars ranged from −4.3 to −6.6, while the largest mass loss rate was 7.1×10^{-5} $M_\odot$ yr^{-1}. The SMC star CV78 has an exceptionally low mass loss rate, 1.8×10^{-7} $M_\odot$ yr^{-1}, for its luminosity, which may be related to its type of SC (Lloyd

Evans 1985b): the low metal content of the SMC and the high proportion of O and C tied up in CO for a star with C/O near to 1.0 leaves little potential to form dust. Feast *et al.* (1982) found that galactic SC stars form a tight group with relatively blue colours in the $(J–H)$, $(H–K)$ and $(J–K)$, $(K–L)$ diagrams, indicating relatively warm photospheres and a lack of circumstellar dust. However one of these stars, UY Cen, has been seen to undergo an apparent dust minimum (Steinfadt *et al.* 2005).

Gruendl *et al.* (2008) found 13 LMC stars with extremely red colours in observations with *Spitzer*-IRAC and MIPS. *Spitzer*-IRS observations revealed absorption of SiC, indicating extremely thick shells around these extreme carbon stars. Initial estimates give luminosities $(4–11) \times 10^3\ L_\odot$ and mass loss rates of 4×10^{-5} to $2 \times 10^{-4}\ M_\odot\ yr^{-1}$.

The driving mechanism of the heavy mass loss on the AGB has been in question. The main alternatives are driving by radiation on the dust and by pulsation; one of the key finding of recent years is the occurrence of a high rate of mass loss for carbon stars, but not for M stars, even if [Fe/H] is low, as it is in the LMC, SMC and other small galaxies. Lagadec & Zijlstra (2008) suggest that the superwind starts when sufficient excess carbon builds up to form much carbonaceous dust, or when the luminosity reaches a value which would drive a silicate dust-driven wind. Groenewegen *et al.* (2007) find that the mass loss rate for carbon stars in the Magellanic Clouds is more closely related to pulsation period than to luminosity. Van Loon *et al.* (2008) show that, so long as dust forms, pulsation rather than stellar luminosity is likely to be the main driver of mass loss.

8.3 *The J-silicate stars*

The circumstellar material generally has the composition of the outer layers of the star, but increasing numbers of stars have been found where this is not the case: this situation is sometimes referred to as mixed chemistry. This first came to light among carbon stars in the discovery (Little-Marenin 1986; Willems & de Jong 1986) of a few with silicate dust emission in their *IRAS*-LRS spectra. Willems & de Jong (1986) noted that two of them were J stars. Confirmation of the O-rich nature of the circumstellar material came from the detection of H_2O maser emission from several of these stars (Nakada *et al.* 1987, 1988). Lloyd Evans (1990) found additional examples in the southern hemisphere; all these stars are J stars and have such red *IRAS* [12]–[25] that they would be optically invisible if they were normal carbon stars with spherical dust shells. Initial explanations in terms of binaries with an M giant companion responsible for the silicate dust or a transitional evolutionary state had various drawbacks, leading to the suggestion that the dust and gas are in a disc (Lloyd Evans 1990; Morris 1990). This suggestion gains support from the observation that many of these stars have a near-infrared excess, which is detectable at L (Lloyd Evans 1990, 1991b and in preparation). The presence of a disc around an evolved star is most easily explained if the star is in a binary system, as the combined gravitational field allows stable orbits for the circumstellar material (Morris 1987). The dust is presumed to be a relic of a mass-loss episode while the star was still O-rich.

Lloyd Evans (1991b) identified a number of optically-discovered carbon stars without *IRAS* – LRS spectra but with very red *IRAS* [12–25] colour. A carbon star of this colour with a spherical shell would not be seen in visible light, but if the dust is in a disk the star may be seen clearly from a sufficiently high viewing inclination. Most of these also had J type spectra; some of the others had weak C_2 and strong Na D lines.

IRAS 12311-3509, a marginal J star with a unique spectrum dominated by emission bands of SiC_2, is a possible example of a J–Si star seen with the disc edge-on (Lloyd Evans *et al.* 2000). The J–Si stars are not uncommon, as they amount to perhaps 10% of all J stars. Some are among the warmer N(J) stars, but there are no definite examples among R(J) stars. The stars which have silicate dust are not distinguishable optically from those which do not have silicate dust (Ohnaka & Tsuji 1999).

Very narrow CO rotational line profiles have been found for BM Gem (Kahane *et al.* 1998) and EU And (Jura & Kahane 1999), suggesting material trapped in a disc. Yamamura *et al.* (2000) show that V778 Cyg most probably has the O-rich material around the unseen companion, providing a reservoir for material to be evaporated by the primary and produce the silicate emission. Szczerba *et al.* (2006) mapped the 22 GHz water emission maser from V778 Cyg and found a distorted S-shaped structure displaced from the position of the carbon star, supporting the model of Yamamura *et al.* (2008). They modeled the water maser structure as a warped disc around the companion in the system, which is seen almost edge-on. Deroo *et al.* (2007) find from interferometry that the system of IRAS 18006-3213 appears asymmetric and probably has a circumbinary disc. V778 Cyg has very strong silicate emission, typical of the outflows from M-type AGB stars and arising from amorphous grains, while IRAS 18006-3213 has a weak emission feature probably arising from crystalline grains. The material acquired from an M-type AGB star would consists of amorphous dust, more of which would be heated to become crystalline in the large region facing the luminous central star in the circumbinary case than in the small region near the faint companion. In the latter case, the spectrum will be dominated by emission from the evaporating outer layers of the disc around the companion.

Izumiura *et al.* (2008) found Balmer and Paschen continuum emission and P Cyg emission lines in the Balmer series for BM Gem, with an outflow velocity of at least 500 km s^{-1}. This is attributed to the presence of a companion, which would have an accretion disc with an ionised gas region and a fast outflow. Ohnaka *et al.* (2008) obtained spectro-interferometric observations of BM Gem across the 10 μm silicate emission feature and found structure in the emission, indicating asymmetry. This was modelled as a circumstellar disc with an asymmetric brightness distribution. The bright region is offset from the star and it was suggested that a disc is centred on the unseen companion. Ohnaka & Boboltz (2008) imaged another J–Si star, EU And, in the 22 GHz H_2O maser and found three maser spots in a shallow S-shape, at $V_{LSR} = -42$, -38 and -34 km s^{-1}, where the middle maser is almost at the stellar velocity. This is interpreted as an edge-on disc, most likely about the companion.

Polycyclic aromatic hydrocarbon (PAH) molecules are found from the infrared spectra of a few carbon stars. One of 50 carbon stars was found to have PAHs in the circumstellar material (Boersma *et al.* 2006): it is TU Tau, which is known to have an A2 companion, whose ultraviolet-rich radiation field is responsible for exciting the infrared fluorescence in this material. The early R star HD 100764 is the other carbon giant presently known to show PAH emission, thought to arise from material in a disk (Sloan *et al.* 2007). The star is slightly variable, with the very unusual feature that the amplitude increases from J to L (Lloyd Evans, unpublished). The variability must lie in the disc, whose infrared excess dominates the flux at L. PAH emission has been found in four of 90 S stars observed by Smolders *et al.* (2010): one is suspected to have a hot companion but the other three, which all have C/O very close to 1.0, follow a relationship between central wavelength of the 7.9 μm PAH feature and photospheric temperature and presumably excite the fluorescent PAH emission themselves.

9. Carbon stars in nearby galaxies

Blanco *et al.* (1978b, 1980) pointed out the large differences, related to metal content, between the number ratio of C to late M stars in the Galaxy, LMC and SMC. Aaronson *et al.* (1982, 1983), who used grisms in the far red to detect strong red CN bands, and Azzopardi *et al.* (1985, 1986), who used an objective grating in the blue-green spectral region, found carbon stars in most of the local group dwarf galaxies which they examined. Aaronson & Mould (1985b) obtained *JHK* photometry for stars in four dwarf spheroidal galaxies which, with published data for another three dSph galaxies, revealed a range of upper giant branch structure. Extended upper giant branches reveal an intermediate age population in Carina, Sculptor, Fornax, Leo I and Leo II, while the giant branches of Draco and Ursa Minor do not extend far beyond the tip of the red giant branch. The luminosity of the brightest star, the mean $(J–K)$ of the carbon stars and their bolometric magnitude were all roughly correlated with the absolute magnitude of the parent galaxy. The carbon stars are of two types, the red N stars of the extended giant branch, formed by the third dredge-up process, and fainter, bluer stars such as those in the Draco dSph galaxy (Aaronson *et al.* 1982), which are probably CH stars.

JHK_s imaging by Menzies *et al.* (2002, 2010) of carbon stars discovered by Azzopardi *et al.* (1986) and by Demers & Battinelli (2002) in the Leo I dSph galaxy showed that they comprise most of the top magnitude of the AGB in this galaxy. Seven much redder stars are spectroscopic or photometric (Held *et al.* 2010) carbon stars and most are Mira variables, some with unusually short periods suggesting great age (Menzies *et al.* 2010), although others are probably the youngest stars in Leo I, with an age of about 2×10^9 yr (Menzies *et al.* 2002). The Phoenix dwarf galaxy contains a probable carbon Mira of $P = 425$ d and two previously known carbon stars, which lie with other stars of unknown type at the top of the AGB, which is not extended in colour (Menzies *et al.* 2008).

The relatively large dSph galaxy in Fornax has an extensive and well populated giant branch with numerous carbon stars found by Westerlund *et al.* (1987) and others. Whitelock *et al.* (2009) obtained JHK_s photometry over three years. Six stars reported as MS, S or SC lie on the upper giant branch, while one is fainter and must be an extrinsic SC star. The mix of S and C stars of comparable luminosity suggests a range of mass or metal content. Periods were found for variables, many of them discovered by Bersier & Wood (2002); seven Miras have periods of 255 to 470 d. Smaller amplitude stars have larger amplitudes, the redder the colour. Several semi-regular variables with probable long secondary periods were found. The Fornax variables tend to be redder at short period than their counterparts in the Galaxy and the LMC.

Cioni & Habing (2003) measured the C/M ratio over the faces of the Magellanic Clouds, using *IJK* photometry to identify M and C stars. The distribution of the C/M ratio over the face of the SMC was clumpy, with no overall trend, but the LMC showed a higher C/M ratio and therefore, lower metal content in an elliptical outer annulus with considerable local variation. A similar exercise for the irregular galaxy NGC 6822 (Cioni & Habing 2005) revealed a large range in derived metallicity, with lower metallicity on either side of the bar.

Demers and Battinelli and their collaborators have searched many of the larger galaxies of the local group for cool carbon stars using the (*CN–TiO*) method. The lists of stars found and the resulting C/M ratio do not always agree well with the results from the near-infrared colours (Battinelli & Demers 2004; Valcheva *et al.* 2007). Comparison of the $(J–K)$ colours with the narrow band data for stars in four nearby galaxies shows that the (*CN–TiO*) method separates C and M stars for $(R–I)_0 > 0.90$, but the hotter carbon stars cannot be distinguished from late K or early M stars, which have similar (*CN–TiO*) indices (Battinelli *et al.* 2007). M stars and the hotter carbon stars overlap in $(J–K)$ and a blue limit is needed to exclude K stars if a true C/M ratio is to be found (Battinelli & Demers 2009). Battinelli & Demers (2005a) calibrate the C/M relationship for 14 galaxies observed by their method. They adopt as a cut-off $(R–I)_0 = 0.90$, which corresponds roughly to M0+, as opposed to the M5 of Blanco *et al.* (1980) which is inappropriate for metal poor systems which contain no late M stars. [Fe/H] declines steeply and almost linearly with increasing log (C/M0+). The C/M ratio is very uncertain for some of the smaller galaxies with low metal content. Battinelli & Demers (2005b) show that the number of carbon stars ranges from two in a galaxy with total absolute V magnitude near −10 to over 10,000 at −18.5. They find only a small dependence of the absolute I magnitude on [Fe/H], such that the carbon stars are slightly brighter, the lower the metal content.

Jackson *et al.* (2007a) obtained *Spitzer*-IRAC photometry at 3.6 and 4.5 μm for the WLM galaxy, in which Battinelli & Demers (2004) had identified carbon stars. The optical survey located only 18% of the total AGB population, while 43% of the AGB stars identified by the infrared survey are too heavily obscured by circumstellar material to be identified optically. The carbon stars which were identified optically are among the bluest and brightest. A great difference between the C/M ratios found by optical and by near-IR surveys of the same galaxy is noted. A similar survey of another dwarf irregular galaxy, IC 1613 (Jackson *et al.* 2007b), yielded very similar results: much of the carbon star population is optically unidentifiable.

Carbon stars in the Magellanic Clouds and their clusters differ from those in the Galaxy in having weak Na I D, weak CN and different near-infrared colours (Lloyd Evans 1980b; Cohen *et al.* 1981; Suntzeff *et al.* 1993). Calculations by Cohen *et al.* (1981) indicated that the colour difference arose from a low N abundance, suggested by Lloyd Evans (1980b). However, Scalo (1973b) notes that the N/C ratio cannot be deduced from the ratio CN/C_2 without a knowledge of O/H and C/O as well. Spectra of stars in both Magellanic Clouds were taken with the infrared spectrometer on *Spitzer* and show enhanced photospheric C_2H_2 and weaker SiC emission at 11.3 μm, indicating that there is relatively less carbon-rich dust in the circumstellar material and correspondingly, more carbon in the stellar atmosphere (Sloan *et al.* 2006, 2008). Matsuura *et al.* (2006), however, found no enhancement in the strength of C_2H_2 in LMC stars relative to those in the Galaxy, but HCN was weak, consistent with the low abundance of nitrogen in the LMC.

10. Evolution

10.1 *Cluster members and their masses*

The N stars were the first to be understood from an evolutionary standpoint. Merrill's (1952) discovery of lines of the radioactive element Tc in the S stars showed that these stars had been producing it recently. The scheme by which an initially O-rich star dredges up carbon and s-process elements, created by thermonuclear reactions in its interior, to become first an S star and then a carbon star, was set out by Cameron (1955). Renzini & Voli (1982) and Iben & Renzini (1982) worked out the detailed theory. Much subsequent work on the abundances, especially of s-process elements, in red giant stars supported this sequence of events, but direct observational proof of the M $\rightarrow$ S $\rightarrow$ C sequence came only with the study of star clusters of intermediate age in the Magellanic Clouds, as galactic star clusters of the relevant age are too small, with at most a single carbon star and no S stars (Bessell *et al.* 1983). Subsequent work (Lloyd Evans 1983a, 1984a; Westerlund *et al.* 1991b) showed that the M $\rightarrow$ S and S $\rightarrow$ C transitions occurred at higher luminosity in the younger clusters. Infrared photometry of almost all the known, accessible upper AGB stars in the intermediate age and old clusters of the Magellanic Clouds were obtained by Mould & Aaronson (1980, 1982); Aaronson & Mould (1982, 1985a); Westerlund *et al.* (1991a) and Frogel *et al.* (1990). The latter, however, refer only to the M $\rightarrow$ C transition, as the grism they used to select AGB stars lacked the resolution to distinguish M and MS stars via the often weak ZrO bands of the latter.

The rich clusters of the Magellanic Clouds do not cover all possibilities, as they belong to a relatively restricted range of intermediate age, with few clusters in a wide interval of age between them and the much older galactic globular clusters. Mucciarelli *et al.* (2009) note the absence of carbon stars in three SMC clusters in the age range (5–7) $\times$ 10^9 yr. Van Loon *et al.* (2005) estimate masses of 1.3 $M_\odot$ for stars in a cluster with age 3 $\times$ 10^9 yr to 6.3 $M_\odot$ at 7 $\times$ 10^7 yr. The latter figure is for a single cluster star; more conservatively, several have values of 4.0 $M_\odot$ at 2 $\times$ 10^8 yr. Lebzelter & Wood (2007) find a pulsation mass of 1.8 $M_\odot$ and an age of 1.4 $\times$ 10^9 yr for the variable stars in NGC 1846. Kamath *et al.* (2010) obtained pulsation masses for stars early on the AGB of 1.55 $M_\odot$ in NGC 1978, of age (1.9–2.2) $\times$ 10^9 yr, and 1.87 $M_\odot$ in NGC 419, of age 1.4 $\times$ 10^9 yr. There have been substantial differences between different sets of isochrones, as well as in observational data, leading to differences in estimated ages and masses.

Feast *et al.* (2006) estimated ages and masses for Mira variables from the kinematics of stars in the galactic field. The mean for carbon Miras is 1.8 $\times$ 10^9 yr and 1.8 $M_\odot$. The longer period stars are younger and more massive.

Carbon stars near the end of their time on the AGB undergo heavy mass loss and surround themselves with dusty, opaque circumstellar material. Such stars are well known from the *IRAS* and other mid-infrared surveys. The original selection of the AGB stars in the clusters of the Magellanic Clouds used photographic plates sensitive to the far red (Lloyd Evans 1980a). Recent surveys with CCD detectors in the near-infrared have revealed small numbers of obscured carbon stars, for instance one each in NGC 419 and 1783 (Tanabé *et al.* 1997) and in NGC 1978 (Frogel *et al.* 1990). More heavily reddened objects were found with *ISOCAM* in the mid-infrared (Tanabé *et al.* 2004).

The lower mass limit for the production of an N-type carbon star has long been known to depend on the initial composition of the star, as the more O it has in the envelope, the more the C which must be added to attain C/O > 1.0. Marigo & Girardi (2007) find that the minimum mass for the M to C transition is 2.0 $M_\odot$ at $Z = 0.019$ but only 0.8 $M_\odot$ at $Z = 0.001$. The figure of 1.3 $M_\odot$ noted above for the LMC falls well within this range, as it should for Z in the region of 0.01. The upper limit of mass would be set by the mass of about 10 $M_\odot$ above which a degenerate carbon core will not develop, were it not for the phenomenon of hot bottom burning (HBB) which burns C into N and O and so may prevent an M star from turning into a carbon star or turn a carbon star back into an M star. A star of 3.5 $M_\odot$ may be turned from a C star back to an M star, and at over 4 $M_\odot$ a star might never become a carbon star. Given all the uncertainties, there is fair agreement between theory and observation.

A search for S stars in galactic globular clusters, for which observations of much higher S/N were possible, proved negative, except for the doubtful presence of marginal MS stars in NGC 6723 (Lloyd Evans 1984b). The CH stars in several clusters, notably Omega Centauri, are probably extrinsic carbon stars. The S stars in Omega Centauri most likely owe their excess s-process elements to a previous generation of stars and not to self-enrichment (Lloyd Evans 1983c). One S star which appears to belong to the galactic halo population has been found (Catchpole & Feast 1971), but an alternative explanation could be that its high velocity indicates membership of an intermediate age population in a small galaxy which has been cannibalised by the Milky Way.

The S stars in the intermediate-age star clusters of the Magellanic Clouds are all mild examples, in the sense that they show TiO as well as ZrO bands and thus are not pure S stars. Also, none are of very late type or are variables of large amplitude, although pure or nearly pure and in some cases highly variable S as well as SC stars are known in the general field of the Magellanic Clouds (e.g., Richer & Frogel 1980; Wood *et al.* 1983; Lloyd Evans 2004). Pure S stars and the intermediate SC and CS stars are probably more massive stars for which a single dredge-up event makes a relatively small change to the C/O ratio, whereas stars which make a large change in C/O at each event may simply jump across the narrow range of values of C/O which correspond to the pure S to CS types.

10.2 *Lithium and carbon stars of high luminosity*

Westerlund *et al.* (1991a) suggest that the high luminosity J-type carbon stars found in the LMC may represent a brief ^{13}C producing stage in the evolution of the more massive AGB stars. This may be identified with the stage of hot bottom burning, when H in the envelope is consumed by the CNO process, leading to a reduction in the $^{12}C/^{13}C$ ratio as well as a reduction in C/O and an increase in the abundance of N (Renzini & Voli 1981). Morgan *et al.* (2003a) have identified in the LMC a group of J stars which are brighter and have stronger CN bands than the N stars and the other J stars. They amount to about 13% of all the J stars and are comparable to the luminous carbon stars found by Westerlund *et al.* (1978), which are mostly J stars (Richer *et al.* 1979). Hartwick & Cowley (1988) and Cowley & Hartwick (1991) identified an overlapping group of carbon stars, selected on blue objective prism plates, which lie to the bright and blue side of most of the N stars in the K, $(J–K)$ diagram (Feast & Whitelock 1992). These authors suggested that they were CH stars, but Suntzeff *et al.* (1993) reported that they are too bright to belong to that group and instead, suggested that they are relatively young carbon stars. Morgan *et al.* (2003a) and Lloyd Evans (unpublished) find that a relatively high proportion, around 30%, are J stars. The Na I D lines are systematically weaker in carbon stars in the Magellanic Clouds (Lloyd Evans 1980b), and in the case of these luminous stars this means that there are none with equivalent widths of the order of 1.0 nm or more, as are found in the Galaxy.

Estimates of mass and luminosity are hard to obtain for stars in the field of the Galaxy; Scalo (1976) assembled data from many sources and concluded that the S and SC stars occupy the same general region of the HR diagram as the N stars. Indirect arguments suggest that S stars with especially strong Na I D lines are of higher luminosity than average (Lloyd Evans & Catchpole 1989).

Strong lithium lines are fairly common among galactic stars of pure S, SC and CS type, as well as carbon stars with weak bands. These stars also have strong Na I D lines in most cases, in accordance with Scalo's (1973a) expectation for stars where C/O is close to unity. Li I is also enhanced for this reason and if the Li abundance is high as well, the 670.7 nm line may be very strong. A few objects with extremely strong Li lines at 670.7 nm are described as Super Lithium Rich (SLR).

Cameron (1955) outlined the way in which ^{7}Li may be produced by burning of ^{3}He and subsequent steps. Smith & Lambert (1989, 1990) found enhanced Li in some MS stars which are probably the most luminous AGB stars in the SMC; some of them are variables of large amplitude (Lloyd Evans 1971) and are too bright to fit the P–L relation so they may be in the HBB stage of evolution (Wood *et al.* 1983). Smith *et al.* (1995) found four SLR stars in the LMC and two in the SMC, while Richer *et al.* (1979) and Richer (1981) found two each, including an SC star (Richer & Frogel 1980) which has the strongest Li line of all, a total of six LMC and two SMC stars after eliminating double counting. Glass & Lloyd Evans (2003) found that two out of five Mira variables which lie above the P–L relation in the LMC have enhanced Li and all have a characteristic light curve, with a bump on the rising branch.

Guandalini (2008) found that SC stars are among the most luminous C stars on the AGB, which also agrees with predictions relating to the much higher abundance of fluorine in an SC star than in typical carbon stars (Abia *et al.* 2010). McSaveney *et al.* (2007) found a very large excess of N in two intermediate mass (4–6 $M_\odot$) AGB stars in the Magellanic Clouds, one of them an MS star with a period of 530 d and a double-humped light curve. This is attributed to the production of primary N by HBB and the third dredge-up.

Hatzidimitriou *et al.* (2003) found 19 Li-rich stars in the LMC among 674 stars examined, but only one of these has Li as strong as the weakest of the SLR stars reported earlier, although the values are reduced by a small amount by more rigorous correction for overlapping CN features. Consequently, it can be said that only three SLR carbon stars are known in the LMC, all with $M_{bol} = -5.0$ or brighter. The Li-rich carbon stars as a whole fall into two groups, with peaks at $M_{bol} = -4.25$ and -5.25, with both J stars and N stars in each group. The 19 Li-rich stars found by Hatzidimitriou *et al.* (2003) include seven J stars, 11% of J stars in the sample, and 12 or 2.2% of ordinary N stars. One of the latter and one of the J stars fall near the top of the tail of hotter and less luminous stars in the sample, with M_{bol} near -3.5. Hot bottom burning may account for the stars of the bright group, but another explanation is required for the fainter stars. Denn *et al.* (1991) obtained Li abundances for galactic carbon stars from high resolution spectra and found no difference in the Li abundances of J stars and ordinary N stars. Abia *et al.* (1993) suggest that Li production in C stars may be a random phenomenon rather than an obligatory stage during AGB evolution, while Wallerstein & Knapp (1998) remarked that evolution may be episodic rather than progressive.

10.3 *The R and J stars*

The distinction between J stars with enhanced ^{13}C and other carbon stars has on occasion been questioned, as the determination of the actual isotope ratio is not straightforward: the early literature shows wide differences in the values obtained for individual stars by different techniques and disagreements continued into more recent times. Lambert *et al.* (1986) obtained $^{12}C/^{13}C$ in the range 3–10 for J stars, whereas N stars had values of 20–90. Abia & Isern (1996) obtained values of 4–9 for J stars, including two with s-process excesses, and 27–47 for four N stars. Ohnaka & Tsuji (1996) obtained values for the N stars ranging from 10 to 60, smaller by factors of 2–3 on average than those found by Lambert *et al.* (1986), but an average value of 22 for SC stars with only three being ^{13}C rich, in contrast to an impression that they are J stars. De Laverny & Gustafsson (1998) suggested that problems with model atmospheres and temperature determination, as well as inadequate spectroscopic resolution, rendered these values doubtful, and preferred the results of Lambert *et al.* (1986). Subsequent papers by Ohnaka & Tsuji (1998) and by De Laverny & Gustafsson (1999) defended their respective approaches, without agreement. Ohnaka *et al.* (2000) used new spectra and methods to obtain values of $^{12}C/^{13}C$ for three stars; the new values are 40% higher and are in closer agreement with the results of Lambert *et al.* (1986). Abia *et al.* (2001) obtained values of 10–90 for N stars, also in broad agreement with Lambert *et al.* (1986). Schöier & Olofsson (2000) determined values of $^{12}C/^{13}C$ for circumstellar material around some of the stars observed both by Lambert *et al.* (1986) and by Ohnaka & Tsuji (1996), from millimetre wave observations of CO lines, with results which agreed well with those of Lambert *et al.* (1986). The hotter R stars and most CH stars have quite weak bands and the J classification cannot be made from spectra of low resolution. Dominy (1984) used spectra of high resolution to find low $^{12}C/^{13}C$ for some early R stars, confirming their relationship with the J star group.

The early R stars have long been known to have relatively low luminosities, as suggested by the similarity of their spectra to those of ordinary giant stars. Baumert (1974) obtained statistical parallaxes for several groups of carbon stars and found that the R stars were 2.6 mag fainter than N stars. Scalo (1976) used several methods to place them quite low on the RGB, in the vicinity of the red giant clump, while the R5 stars, as classified by Cannon & Pickering (1918), which are nearly all J stars, are three magnitudes brighter. The Hipparcos satellite provided trigonometric parallaxes for many of these stars and Knapp *et al.* (2001) used these to confirm that the early R stars lie in the region of the red giant clump. There are too few late type R stars with satisfactory parallaxes to give a definitive result, but they extend to higher luminosity and lower $T_{\rm eff}$. Restriction of the class of R stars to those which have enhanced ^{13}C and the addition of J stars classified as N stars shows a continuous distribution in those colours which show a general trend with $T_{\rm eff}$; a larger sample would be useful to establish this more securely. The R5 stars overlap in colour with the warmer N-type J stars as a result of errors in the spectral classifications.

The hottest R stars have very weak bands, indeed there are a few which are probably misclassified ordinary G or K giants or CH stars (Zamora *et al.* 2009), and it may be asked whether there might not be unrecognised examples of stars with enhanced C at higher $T_{\rm eff}$ further down the giant branch, so that the concentration of the early R stars to the region of the red giant clump might be an artefact of classification. The rarity of early R stars, only 0.04% of the red giant clump stars in the solar neighbourhood

(Knapp *et al.* 2001), means that none are known in star clusters, while only a very few relatively luminous, late type R stars have been found in the Magellanic Clouds (Richer 1981; Bessell *et al.* 1983; Westerlund *et al.* 1991b).

Morgan *et al.* (2003a) found 156 J stars in the LMC, out of a total observed sample of 1497 N-type carbon stars. A measure of the relative strengths of the isotopic bands gave a bimodal distribution, confirming the clear distinction between J and N stars on spectra of moderate resolution when the star is cool enough to show strong bands. The J stars are about 0.6 mag fainter in K at a given $(J{-}K)$, except for the 13% in the bright group described above. These differences between the J stars and the ordinary N stars support the idea that they follow different evolutionary paths. Westerlund *et al.* (1991a) suggested the paths, M $\rightarrow$ S $\rightarrow$ C(wk C_2) $\rightarrow$ C and M $\rightarrow$ J $\rightarrow$ C. However, it seems more in accordance with the observations if the J stars never pass through the M star stage, but climb the giant branch, from at least the level of the red giant branch clump, as carbon stars with enhanced ^{13}C. This is the evolutionary path R(J) $\rightarrow$ N(J).

The distinction between N and N(J) stars is also clear in the s-process abundances, which are enhanced by factors of order five in the ordinary N stars (Abia *et al.* 2001; Zamora *et al.* 2009) but not in the J stars (Utsumi 1985, 1988; Abia & Isern 2000).

McClure (1997) found no evidence of binary motion in any of 22 R stars observed over a 16 year period. He suggested that they might have been formed as binaries with separations which lead to coalescence before the AGB stage was completed. Carbon produced in the He-core flash might be brought to the surface as a result of this coalescence. Izzard *et al.* (2007) have examined many binary models to assess a variety of possible evolutionary paths by which stars may merge and produce an R star. Angelou & Lattanzio (2008) consider the mechanism by which CNO cycling and carbon dredge-up could occur in such merger products. The alternative hypothesis for the production of R stars is that the He-core flash occurs in an abnormal way, possibly ignited off centre. Cole & Deupree (1980) made models which show that the helium flash may initiate partial mixing of the star in some cases.

10.4 *Hydrogen-deficient carbon stars*

The HdC and RCB stars are understood as luminous objects in a very rare state of evolution, having returned to a high luminosity from a degenerate stage of evolution. Two models have been proposed: the Double Degenerate (DD) and the Final Helium Flash (FF) models. The first requires two white dwarfs to merge and the second invokes a late helium shell flash to return a white dwarf to the dimensions of a supergiant. Clayton (1996) reviews the details. A possibly decisive observation in choosing between the two models is the great excess of ^{18}O found in the HdC star HD 137613 (Clayton *et al.* 2005) and in four RCB stars and another three HdC stars (Clayton *et al.* 2007). Model calculations appear to rule out the FF model as unable to match the low ^{16}O/^{18}O and high ^{12}C/^{13}C values observed in these stars, whereas a merger of a CO-WD with a He-WD may do so. Another critical observation is the very large overabundance of F in RCB stars (Pandey *et al.* 2008), which is also predicted (Clayton *et al.* 2007) for the DD model but not the FF model.

11. Outstanding problems

There are of course many remaining problems, as much because of recent progress as in spite of it. Much will be done with the new techniques and facilities available now and these will raise new questions. A short personal selection of identifiable problems includes the following. The CH stars are understood in principle, but there is much to do, especially in connection with the abundances and the very metal poor CEMP stars. The origin of the J stars is only now being tackled; much more needs to be done before the exact sequence of events involved can be established. The origin of the J-silicate stars is even more obscure: it seems reasonable that the retention of O-rich material in a disc arises from the presence of a companion star, but why do so few ordinary N stars have disks? Most giant stars with material in a disc have attracted the attention by emission lines or variability, as in the case of symbiotic stars. The part played by binaries at all stages in the life of a carbon star needs to be better understood: binarity among the post-AGB stars seems to be associated mainly with O-rich stars. The main features of mass loss are becoming clearer, but the remarkable detached shells around stars such as U Ant still raise questions, while the evolutionary significance of the observable dust events in carbon Miras (R Lep) and the spectroscopically distinct events in T Mus are uncertain. The study of ongoing mass loss requires sustained observation over years and decades and the greater use of high angular resolution and of polarimetry as well as of spectroscopy.

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