167. Carbon stars

CARBON STARS are characterised by atmospheres with more carbon than oxygen. The 'classical' carbon stars are luminous red giants, on the asymptotic giant branch. Their plentiful atmospheric carbon gives them a deep red appearance, and they were first recognised spectroscopically by Angelo Secchi in the 1860s.

Intrinsic carbon stars arise as a result of carbon being 'dredged up' from their core at certain evolutionary phases. But some (extrinsic) dwarfs and supergiants may also show C/O>1 as a result of mass transfer from a carbon-enriched binary companion.

The abundant C combines with any O in the cooler upper layers to form CO. Residual carbon forms other C-based compounds, and results in a 'sooty' atmosphere and a vivid red colour. Spectroscopically, they include the C_2 (Swan) absorption bands at 438.3 and 473.7 nm, and the 421.6 nm band of CN. They are typically long-period variables, and include the C-rich Mira variables.

Apart from their high carbon content, their spectral properties broadly parallel main sequence K–M stars. They are sub-divided into the 'warmer' (and rarer) R stars (the carbon analogue of K stars), and the 'cooler' N stars (the carbon analogue of M stars), and others.

TO EXPLAIN HOW the excess C abundance arises, I will greatly simplify the complex post-main sequence evolution of intermediate mass stars (see figures).

Following core H exhaustion, the core contracts and heats, causing the outer layers to expand and cool, and the star develops into a red giant. Once He-core burning starts, the cooling halts, and the star moves 'down and left' on the *horizontal branch*. On completion of core He-burning, the star moves 'up and right' again – cooling, expanding and increasing in luminosity along the *asymptotic giant branch*, or AGB.

During a series of short-duration thermal pulses, which result from a complex interplay between cycles of H- and He-shell burning, deep convection 'dredges up' core material. It is the phenomenologically-defined 'third dredge-up' which brings He, C, and the various s-process elements to the surface, increasing the C/O ratio, and turning the star into a carbon star.

THEORY SUGGESTS that essentially all stars with initial masses $1.5 - 4 M_\odot$ should go through the carbon star phase, lasting around 300 000 yr, before ending as a white dwarf. Their very high luminosity makes them important for integrated light studies of galaxies, and they have also been considered as potential standard distance indicators, along the lines of the Cepheids, TRGB, or JAGB (Richer, 1981; Battinelli & Demers, 2005; Freedman & Madore, 2020; Ripoche et al., 2020).

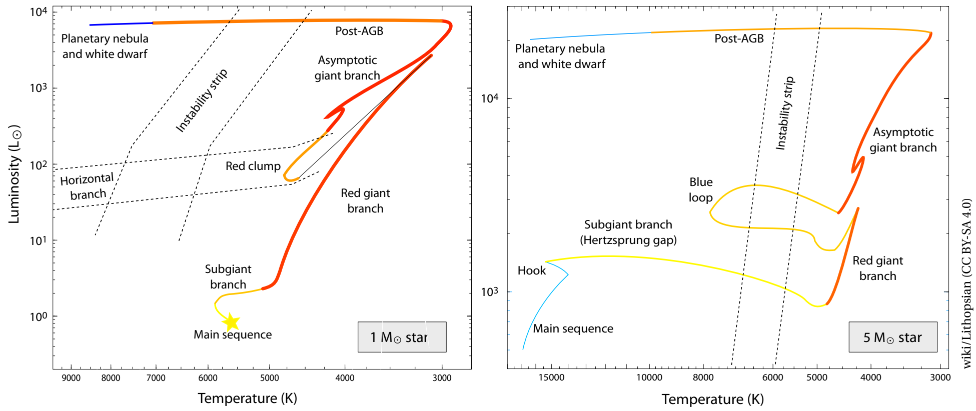
Their chemical compositions are typically nearly solar C/H, N/H, and $^{12}C/^{13}C$ ratios, indicating that much of the C and N in our Galaxy came from mass-losing carbon stars. Their mass-loss rates, up to several times $10^{-5} M_\odot\,\mathrm{yr}^{-1}$, contribute around half of the total mass returned to the interstellar medium (Wallerstein & Knapp, 1998; Straniero et al., 2023). Carbon stars are also among the main sites of heavy-element production ($A \geq 90$), through the (slow neutron capture) s-process.

TODAY, there are thousands of known carbon stars: the Third Edition of the Catalog of Galactic Carbon Stars by Alksnis et al. (2001) listed 6891. A recent catalogue of AGB stars in our Galaxy by Suh (2021) lists 11 209 O-rich and 7172 C-rich. Other compilations include those by Chen & Yang (2012) and Ji et al. (2016).

Some of the brighter and more well-known carbon stars include (wiki links provided): V Aql, Y CVn, CW Leo, R Lep, SS Vir, and TX Psc.

No individual distances were known before Hipparcos and Gaia. But even if a distance is known, and therefore an absolute magnitude, assigning an individual mass is usually impossible, and it is parameters such as mass-loss rate and age that are some of the weakest links in current model predictions (Abia et al., 2020).

SOME 320 carbon stars were identified in the Hipparcos catalogue by Knapp et al. (2001). Of the R stars (the least understood, and whose knowledge is, in part, limited by distance uncertainties) just 17 had $\sigma_\pi/\pi < 0.5$. Knapik et al. (1998) estimated a local space density of $40 - 70\,\mathrm{kpc}^{-3}$, with no clear spatial correlation with the local spiral arm structure or interstellar extinction.



In their detailed review of the present state of knowledge, both theory and observation, Straniero et al. (2023) noted: *'More than 40 years after the pioneering paper by Iben (1981), the efficiency of the third dredge-up and the chemical yields from AGB stars are still burdened by heavy uncertainties and disagreements among different authors, mainly due to the lack of a robust theory of convection and mass loss.'*

For example, the number of thermal pulses required to yield C/O>1 is a complex function of initial mass, metallicity, dredge-up efficiency, mixing-length and convective overshoot parameters.

It is these sorts of uncertainties, poorly constrained by calibrated luminosities given their large distances, that propagate through to uncertainties in chemical enrichment models, and thus to the chemo-dynamical history of the Galaxy (e.g. Gustafsson, 2022).

Turning to Gaia, the 'Golden Sample' of Creevey et al. (2023; see also essay 90) used all relevant Gaia data (astrometry, photometry, and the mean BP/RP and RVS spectra) to define various well-defined subsets, including a sample of 15 740 carbon stars. It reveals a strong concentration towards the Galactic plane, with others in the LMC/SMC, and the Sagittarius stream.

Various studies have been made using Gaia data. Kostandyan (2020) used DR2 to study 127 carbon stars ($G = 9-18$ mag) discovered from the First Byurakan Survey, of which 56 are N type. All are AGB stars in the Galactic halo, all within 14 kpc, all within 8 kpc of the mid-plane, and with radial velocities available for 75.

Pal & Worthey (2021) tackled the uncertain age dilemma by selecting carbon stars associated with clusters and moving groups of known age, and investigated the occurrence of Galactic carbon stars as a function of progenitor mass using the Gaia DR2 data. Amongst their conclusions, the C-star frequency agrees with that observed in the Magellanic Clouds down to $1.67 M_\odot$, as does the frequency of carbon stars in M31.

Abia et al. (2020) also used DR2 to determine the luminosity function and kinematics of 210 carbon stars in the solar neighbourhood with $\sigma_\pi/\pi < 0.2$. Amongst their conclusions were that most of the N type stars belong to the thin disk population, while a significant fraction of the R type are compatible with the thick disk.

Abia et al. (2022) extended these studies using EDR3, and a larger sample of 974 C stars (491 N type, 22 SC, 83 J, 234 R, and 276 CH). Amongst their conclusions, they found that N- and SC-type stars share a similar luminosity function, while the R type have luminosities throughout the red giant branch, favouring an external origin for their C enhancement. They identified 2660 new C stars through their 2MASS photometry and Gaia astrometry.

The AGB stars, and in particular the J-region (JAGB) method (Freedman & Madore, 2020, §2.1), have considerable potential as an extragalactic standard candle, capable of calibrating the absolute magnitudes of local Type Ia supernovae, and thus an independent determination of the Hubble constant. The topic is already a substantial field of study (e.g. Lee et al., 2021; Lee, 2023), which I will not detail further here.

A study by Nanni (2019) characterised the properties of amorphous carbon dust condensed around carbon stars by comparing the LMC carbon stars (from 2MASS and Gaia DR2) with synthetic photometry from dust growth models. Only very specific combinations of optical data and grain size could simultaneously match the infrared photometry and Gaia astrometry.

Roulston et al. (2021) focussed on dwarf carbon (dC) stars, main-sequence stars enriched by mass transfer from a carbon-rich (AGB) companion, itself since evolved to a white dwarf. Their investigations focussed on their orbital properties, derived from the photometric light curves from the Zwicky Transient Facility for a sample of 944 dC stars. They used the Gaia EDR3 parallaxes and proper motions to verify that any periodic (orbit) candidate was indeed a dwarf carbon star.