Session XI

GALACTIC CHEMICAL EVOLUTION

“Duck Soup” – One of the stories of the 14th-century folk teacher/preacher Nasrettin Hoca, as envisaged by Bengt Gustafsson (see p. 494).

CARBON STARS AND NUCLEOSYNTHESIS IN GALAXIES

BENGT GUSTAFSSON AND NILS RYDE
Uppsala Astronomical Observatory, Uppsala, Sweden

Abstract. The role of carbon stars in the build-up of chemical elements in galaxies is discussed on the basis of stellar evolution calculations and estimated stellar yields, abundance analyses of AGB stars, galactic-evolution models and abundance trends among solar-type disk stars. We conclude that the AGB stars in general, and carbon stars in particular, probably are main contributors of *s*-elements, that their contributions of flourine and carbon are quite significant, and that possibly their contributions of lithium, ^{13}C and ^{22}Ne are of some importance. Also contributions of N, Na and Al are discussed. The major uncertainties that characterize almost any statement concerning these issues are underlined.

1. Introduction

Any discussion of the role of carbon stars (C stars) in the chemical evolution of galaxies raises a number of important questions such as: For which metal abundances and initial stellar masses do stars become C stars? How much mass does a star lose during its C star phase? What are the elemental compositions of these ejecta?

C stars are brilliant and show easily recognizable spectral characteristics. Thus, their occurrence and frequency in different galaxies may be interpreted in terms of the properties (metallicity and age) of the stellar populations, if we know which stars become C stars. Current answers to this question are, however, not very precise, although stars with masses somewhere in the interval 1.2 to $4\,M_{\odot}$ may be a realistic answer. Studies of the distribution of C stars perpendicular to the Galactic plane suggest typical masses in the interval 1.2 – $1.6\,M_{\odot}$ (Claussen et al. 1987; cf. also Groenewegen et al. 1995). For stellar masses greater than about $4\,M_{\odot}$ hot-bottom burning (HBB) is thought to prevent C star formation (Boothroyd et al. 1993). In metal-poor populations, stars with even smaller masses

R.F. Wing (ed.), The Carbon Star Phenomenon, 481-496.

may become sufficiently carbon-enriched to show C star spectra, while HBB may also be effective in inhibiting C star formation at lower masses than for Pop. I stars. An important issue in this respect is the frequency of C-rich planetary nebulae (PNe) in the Galaxy, which is so high (cf. Zuckerman & Aller 1986; Rola & Strasińska 1994) that a considerable fraction of all stars must become C stars in the end — this is a strong reason for not increasing the lower limit of the mass range discussed here too much above $1\,M_\odot$.

There is consensus that mass loss probably both sets the maximum luminosity that a star achieves and determines the time it spends in its evolution up along the AGB. The total mass returned to the interstellar medium is obviously the difference between the initial stellar mass and the final remnant mass (typically about $0.65\,M_\odot$ for the stars discussed here). In order to determine the total mass lost from the C stars we first need to know how much mass these stars have lost before becoming C stars. Most authors assume that the total mass loss on the RGB is on the order of $0.2\,M_\odot$ for solar-mass stars, following arguments by Renzini & Fusi Pecci (1988), while more massive stars — being more compact and not undergoing the He core flash — presumably lose less. Many studies also assume some continuous mass loss, specified by the Reimers relation (with a suitable fitting parameter), followed at the end of the AGB by a "superwind" with a steeper dependence of mass loss on stellar parameters. Detailed models of pulsating stars (Bowen & Willson 1991; Willson et al. 1996) demonstrate the inadequacy of simple parametrizations — the mass loss rate turns out to be quite sensitive to stellar parameters, including mass and composition, and this cannot be determined empirically from available observed mass loss rates because the stellar parameters are not well known.

Since the atmospheres of AGB stars, and especially C stars, are enriched in many elements by interior nucleosynthesis and various mixing mechanisms, they contribute substantial amounts of heavy elements to the interstellar medium (ISM). (Also, the physical and chemical properties of the ISM are affected by the grains produced by C stars.) The main yield to the ISM from the C stars depends, however, on the interplay between mass loss and dredge-up of processed material from the inner stellar layers. Neither of these processes is very well understood. In recent model calculations dredge-up, as well as mass loss, is incorporated with free parameters adjusted to fit some selected observational constraints, such as the luminosity distribution of C stars in the Large Magellanic Cloud (LMC). Major recent contributions of this type are due to Groenewegen & de Jong (1993), Groenewegen et al. (1995), Blöcker (1995) and Marigo et al. (1996). This may be a questionable procedure in view of the assumptions made concerning the dependence of the adjustable parameters on stellar properties.

Key issues in the present discussion are when, during the AGB evolution with its gradual dredge-up of enriched material, the most significant mass loss occurs and how this depends on the metallicity of the star. We are still far from definitive answers to these questions. Here, a rather empirical discussion will be given, based on the observed chemical compositions of stars and PNe. For a detailed and more theoretical approach, based on calculations of nuclear processing and mixing during the AGB with adjustable parameters describing the dredge-up as well as with semiempirical recipes for mass loss rate as a function of luminosity and pulsation period, see Marigo et al. (1996). These authors also contribute tables of predicted yields, partially superseding those of Renzini & Voli (1981).

Another, more indirect but very significant basis for estimating yields will also be used below: the trends in relative abundances of solar-type stars of different ages in the solar neighborhood. From such results (e.g. those of Edvardsson et al. 1993) one can estimate relative time scales of the build-up of different elements, and thus separate the contribution of elements from, say, slowly evolving low mass stars as compared with contributions from rapidly evolving high mass stars through supernova (SN) explosions.

We shall here review the current knowledge, and lack of knowledge, as regards the role of C star production of the nuclei of Li, C, N, O, F, Ne, Na, and Al as well as of the *s*-process elements. Our discussion will be based on what is known from stars in the galactic disk and in the LMC, and it is important to stress that the understanding concerning the mechanisms of the formation, nucleosynthesis and mass loss of C stars is so weak that extrapolations to stellar populations with other properties are highly uncertain. In fact, the mixture of arguments, partly based on galactic, partly on LMC C stars, in contemporary discussions is in itself dangerous, but necessary.

2. Nucleosynthesis

2.1. LITHIUM

As has been demonstrated by Reeves et al. (1990), spallation of CNO nuclei in the interstellar medium, although contributing ^{6}Li, Be and B, cannot be the main process for raising the ^{7}Li abundance from the Pop. II plateau value found by Spite & Spite (1982) to the more than 10 times higher value found in the solar system and in young stars. The processes by which Li has been built up are as yet not determined, but several processes have been proposed: Li-production in AGB stars, the ν-process in SNe of Type II (SNeII), and production in novae. In a study based on models of galactic chemical evolution and observed abundances of light elements, Brown (1992) suggested intermediate-mass stars to be main contributors.

Some C stars show very strong Li I resonance lines (McKellar 1940) and these stars have been proposed to be a significant source of Li to the ISM (Scalo 1976). These rare stars, having logarithmic Li abundances, log ϵ(Li), of about 10 times the solar system value or even greater (~ 4 on a scale with log ϵ(H) set to 12), are still not fully understood; attempts to explain them include HBB and the Be transport mechanism of Cameron & Fowler (1971) (Sackmann & Boothroyd 1992; Abia et al. 1993b).

Abia & Isern (1996) found that the ^{13}C abundances of galactic C stars correlate with their Li abundances; this may give a further clue to the origin of the super Li-rich phenomenon. These authors suggest that HBB might produce the abundances found if one invokes a more efficient convection than is usually assumed. This could decrease the lower mass limit of HBB to below $2\,M_\odot$. Alternatively, the plume mixing model of Scalo & Ulrich (1973) might operate in these stars.

The significance of C stars in general for galactic Li production is entirely dependent on the role of the super Li-rich stars; the more normal N stars have log ϵ(Li) ranging from −2 to 2 (Abia et al. 1993b) which is far too low for the stars to be of significance in this respect. Key questions concerning the super Li-rich stars are: (1) How common are they? (Note that the conclusion of Abia et al. that these stars may provide a significant fraction of the galactic Li is based on only one star!) (2) How does their frequency depend on mass, metallicity and other parameters? (3) What are their true Li abundances? (We note that the abundance estimates are severely dependent on model atmospheres, spectral synthesis and adopted C/O ratios for the models. Thus, Abia et al. (1993a) derive an abundance for WZ Cas of log ϵ(Li) $= 5$, while Boesgaard et al. (1996) find a 3 times lower abundance with the same grid of model atmospheres.) (4) Are the super Li-rich stars overrepresented, or represented at all, among the dust-enshrouded stars with mass loss rates $> 10^{-5}\,M_\odot$/year? (5) Do the super Li-rich stars represent relatively short episodes, followed by Li burning, and certain limited mass intervals — as is suggested by the model calculations by Sackmann & Boothroyd (1992) and Frost & Lattanzio (1996) — or could they possibly mark the ending stage of AGB evolution in general?

A conclusion in several studies is that the C stars probably do not contribute significant amounts of Li (cf. Matteucci et al. 1995), even though contributions as high as 30% or more of the interstellar Li may be possible if some super Li-rich stars also have high mass-loss rates (cf. Abia et al. 1993b).

An interesting issue is whether this situation is different for low metallicities — i.e., in early phases of galactic evolution or in the present evolution of dwarf galaxies. A low metal abundance seems to lead to HBB at smaller stellar masses (cf. Sackmann & Boothroyd 1992). On the other hand, the low metallicity stars may lose their mass at lower rates, such that the Li produced may be burnt away before most of the mass loss occurs (Matteucci et al. 1995). Empirical support for this may be the Li abundance of log ϵ(Li) ≈ 3 derived for luminous AGB (S) stars in the SMC (with a metallicity 1/3 of solar) found by Plez et al. (1993), which, in spite of being significantly higher than expected from standard AGB evolution is still lower than values for the most Li-rich AGB stars in the Galaxy.

In conclusion it seems probable that another process, such as the ν-process in SNeII (Woosley et al. 1990), is the main mechanism responsible for Li formation. However, until we understand the nature of the super-Li rich C stars better, more definitive statements must be avoided.

2.2. CARBON

For some time, intermediate or low mass stars have been considered as probably important for the production of carbon in the Galaxy (see, e.g., Tinsley 1978). Sarmiento & Peimbert (1985) estimated the carbon contribution from AGB stars to be on the order of 60–80% of all galactic carbon. Their argument was essentially based on the fact that models of SNe and novae suggested that these objects could not produce more than a minor part of the carbon in the interstellar medium. Sackmann & Boothroyd (1991) claimed, on the basis of calculations of dredge-up of carbon in AGB model sequences, that low and intermediate mass AGB stars are the dominant sources of carbon in the universe. The more recent supernova models of Woosley & Weaver (1995) and Thielemann et al. (1996) predict yields that are mutually different by about a factor of two, the Thielemann et al. yields being lower due to a high rate for the ^{12}C(α,γ)^{16}O reaction. Adopting the higher yields of Woosley & Weaver (1995), Timmes et al. (1995) still find in their models of galactic evolution that SNe and novae cannot produce enough, so that the contributions from stars with a mass less than 11 $M_{\odot}$ must be dominant. Timmes et al. also adopt the (now partly obsolete) yields from intermediate and low mass stars of Renzini & Voli (1981) and find that the carbon abundance relative to iron, [C/Fe], was lower by about a factor of two than its present value in the early evolution of our galactic disk; then it increased above its present value and finally decreased again as a result of iron production in less massive SNeIa.

This particular behavior of [C/Fe] relative to [Fe/H] is not seen in the composition of solar-type disk stars of different ages, according to Tomkin et al. (1995). Instead, these authors find a steady decrease in [C/Fe] *vs.* [Fe/H], suggesting a less dramatic variation of contributing sites during the history of the Galaxy. In fact, the ratios of carbon relative to oxygen and α-elements (produced in SNeII) only vary slowly and smoothly with [Fe/H]. This suggests that the carbon may well have been produced in high-mass stars, although carbon does not follow oxygen in the halo (Tomkin et al. 1992), nor in dwarf galaxies (Garnett et al. 1995). The decrease of [C/Fe] with increasing [Fe/H] in the galactic disk is very different from the variation of the *s*-element abundances with [Fe/H] (see also Edvardsson et al. 1993). This suggests that the *s*-elements were formed in stars with considerably longer characteristic lifetimes, i.e. smaller masses.

Prantzos et al. (1994) studied the formation of oxygen and carbon in the Galaxy and found that, if the duration of the halo phase was on the order of 1–2 Gyears as is currently believed, intermediate or low mass stars should not have been the main carbon sources. Instead, these authors suggest that massive stars contribute with metal-dependent yields (Maeder 1992). We note that the model calculations of Prantzos et al., with contributions added also from the intermediate and low mass stars according to Renzini & Voli (1981), fit the results of Tomkin et al. (1995) rather well, although the C/O ratios of comparatively metal-rich halo stars become too high. In that model, about 40% of the carbon in the disk stars was contributed by intermediate and low mass stars. Adoption of the yields of Marigo et al. (1996) would diminish the discrepancy for the metal-rich halo stars but may produce too much carbon at late stages.

Other data suggest that the intermediate and low mass stars may play a significant role in carbon synthesis. Adopting the findings by Zuckerman & Aller (1986) and Rola & Strasińska (1994) that about half of the PNe have $C/O > 1$, we find that these stars should contribute at least about $0.001\,M_{\odot}$/year of carbon to the Galaxy. (Here, we have used the PNe birthrate of about 1 PN per year in the Galaxy estimated by Pottasch (1992), and a characteristic PN mass of $0.3\,M_{\odot}$.) Assuming the yields recently derived from a semi-empirical modelling of the AGB phase by Marigo et al. (1996) would presently give contributions on the order of $0.003\,M_{\odot}$, depending on the star formation rate adopted. This contribution is of the same order of magnitude as the total present contribution by SNeII, assuming yields from Woosley & Weaver (1995) and a SN rate of 3 per century. In making this estimate we have assumed a closed box model; this may overestimate the significance of SNe relative to PNe, in view of the much higher expansion velocities of material ejected in SNe. One should note that the number of C-rich PNe is so high that they cannot only be produced by intermediate-mass stars; a significant fraction of the C-rich PNe must be formed by stars in the mass interval between 1 and $2\,M_{\odot}$.

If low-mass stars are assumed to produce significant amounts of carbon, further discrepancies between models of galactic chemical evolution and observed abundances may occur in the relative-abundance diagrams, such as those of Tomkin et al. (1995). Possibly, this conflict could be resolved by advocating more efficient carbon production by intermediate and low mass metal-poor stars, following the discussion of Boothroyd & Sackmann (1988) that suggests a more efficient dredge-up of carbon for models with low abundances of heavy elements. We note that the carbon yields by Marigo et al. (1996) are several times greater at a given initial stellar mass for their metal-poor (Z=0.008) models than for their Pop. I (Z=0.02) models. (This is, however, dependent on the assumptions made in these models that the two adjustable third-dredge-up parameters, the minimum core mass for dredge-up and the dredge-up efficiency, are independent of metallicity, and that the mass loss rate is dependent only on the metallicity through its effects on evolutionary tracks and pulsation period.) Another possibility, which should be further investigated, is that the spectrum analysis of the high-excitation C I lines in solar-type stars may give systematic errors, different for stars of different metallicities, e.g. due to errors in the effective temperature scale, or errors due to inhomogeneities and departures from LTE (we note, however, the small non-LTE effects found for carbon in the Sun by Stürenburg & Holweger 1990). The study of Andersson & Edvardsson (1994), using the low excitation [C I] line at 8727 Å, seems to verify the results of Tomkin et al. but the weakness of that line only admitted upper limits for most of the metal-poor disk stars in their sample. Further studies based on this line with higher S/N are underway.

Do the C stars contribute significantly to galactic carbon? Number densities and mass-loss observations of bright, as well as dust-enshrouded, C stars in the Galaxy (Olofsson et al. 1993a, 1996; Jura & Kleinmann 1989) suggest a total contribution of about $2 \times 10^{-4}\, M_{\odot}$/year. The indication, from the statistics of PNe, that C stars may contribute one order of magnitude more is the result of the fact that about every second PN is carbon rich. This illustrates the key significance, mentioned in the Introduction, of the question of the chemical composition of the stellar envelope just prior to the extensive mass loss that ends the AGB evolution.

We conclude that the significance of low and intermediate mass stars for carbon synthesis is still unclear, and deserves further exploration.

2.3. THE CARBON ISOTOPE ^{13}C

Prantzos et al. (1996) have discussed the observations of carbon isotope ratios in the galactic disk and conclude that ^{13}C has probably a mixed origin, being produced both as a primary element — presumably in intermediate-mass stars by HBB or by other processes where protons are mixed with ^{12}C produced in the star by He burning — and as a secondary element by CN burning, occurring in stars of all masses. The ^{12}C/^{13}C ratios observed in C stars range in the interval 30–100, with a pronouced peak around 50 (Lambert et al. 1986; a lower range, 15–40, has, however, been obtained by Ohnaka & Tsuji 1996, and these differences need further exploration). Excluded from this is a minority of J–type stars with considerably lower ratios. Values around 50 are consistent with the C/O ratios derived by Lambert et al.; that is, the result may be explained as the consequence of mixing ^{12}C to the surface layers if ^{13}C is left from the first dredge-up. These values agree reasonably well with those (30–40) derived for dusty C stars from mm-line observations by Kahane et al. (1992). These authors have also observed the C-rich PN NGC 7027 and find a $^{12}C/^{13}C$ lower limit of 65. In fact, the difference in C/O ratio between bright N stars and C-rich PNe (see Lambert et al. 1986) suggests that further ^{12}C enrichment has taken place in the latter, which would correspond to an increase from 50 to about 80 in $^{12}C/^{13}C$. Although this agrees with the local ISM value, that may well be fortuitous — little is known about the $^{12}C/^{13}C$ ratios in PNe. One should also note that the ^{13}C "produced" by normal C stars is, as presumed above, just the result of the CNO burning and the first dredge-up. That is, however, not necessarily the case; we note that Plez et al. (1993) find low $^{12}C/^{13}C$ ratios for S stars in the Small Magellanic Cloud indicating H-burning in the envelope in late evolutionary phases.

One might ask what the role of the extremely ^{13}C-rich J stars may be in providing ^{13}C. The evolutionary history of these stars is still not understood (cf. Lambert et al. 1986 for some suggestions). They constitute about 1/5 of the bright N–type stars in the magnitude-limited Lambert et al. sample and have a $^{12}C/^{13}C$ ratio of typically 5. They tend, however, to be systematically oxygen-poor; therefore, the ^{13}C abundances relative to hydrogen are not more than typically a factor of 5 higher than those of other C stars. The J–type stars do not show any tendency of having higher present mass-loss rates than the rest of the N stars (Olofsson et al. 1993a). From this one would only conclude that the J stars at present contribute approximately the same total amount of ^{13}C as the rest of the visible N stars. Similarily, if the J–type stars lose their envelopes without first burning their ^{13}C, and if the fraction of J stars among C stars of 20% really is representative also of the population of immediate progenitors of C-rich PNe, which is highly questionable, the J stars could then deliver as much ^{13}C as the sum of the rest of the C stars. There is at least one additional circumstance that might suggest that the J–type stars play a significant role in this respect: a great fraction of the most luminous red AGB stars in the LMC are ^{13}C-rich C stars (Richer et al. 1979), possibly indicating that a greater fraction than 20% of the more massive C stars reach this stage close to the end of their AGB evolution, at least in metal-poor populations. However, there is also a population of low-luminosity J–type stars present (cf. Richer 1981; Bessell et al. 1983) which does not necessarily correspond to the latest phases of AGB evolution. Brewer (1996) recently discovered 7 J–type stars among 48 C stars in two M31 fields and found the J stars relatively faint.

2.4. NITROGEN

^{14}N is thought to be produced by equilibrium CNO–burning in the hydrogen burning shell, brought to the surface layers at the first dredge-up and even more at the second dredge-up, occurring in stars of 4–8 $M_{\odot}$ and expelled during later stellar evolution. Timmes et al. (1995), however, conclude, on the basis of abundance trends among galactic stars and radial gradients of CNO abundances in H II regions in galaxies, that ^{14}N has a strong primary component which they ascribe to low metallicity massive stars. Woosley & Weaver (1995) show that it is possible to create this isotope in massive stars and claim that approximatively 25% of the solar abundance can be ascribed to these sites. Vila-Costas & Edmunds (1993) show evidence for a delayed primary and a secondary component relative to oxygen, the delay indicating that intermediate mass stars are responsible. The low N/O ratio observed for a high redshift gas cloud by Pettini et al. (1995) also supports an intermediate-mass primary component. The secondary component is dominant at high metallicities. The bulk of the solar abundance of ^{14}N is attributed to low and intermediate mass stars (see e.g. Timmes et al. 1995).

Empirically, the evidence that C stars contribute a significant extra amount of N is weak. Lambert et al. (1986) find, from their analyses of CN lines in N–type star spectra, that these stars are not very N-rich, and this result is strengthened by recent values of the dissociation energy of CN. Olofsson et al. (1993b) find an N abundance higher by about a factor of 5 or so from their analysis of HCN mm lines from the circumstellar envelopes of the same sample of N stars, but this may be due to an underestimated mass loss rate (cf. also Olofsson et al. 1996). The C-rich PNe are, according to Zuckerman & Aller (1986), generally not very enriched in N — only very few in their list have N abundances in excess of twice the solar value. Pasquali & Perinotto (1993) list a mean nitrogen abundance of twice solar for their C-rich PNe of type II and III, which represent disk stars of intermediate and low mass, while the mean N abundance given for PNe of type I, that are more carbon-poor and represent younger, more massive objects, is three times greater. Kingsburgh & Barlow (1994) give a mean nitrogen abundance of only 1.4 times solar for their 36 non-Type I PNe. Similar tendencies may be traced in the yields calculated by Marigo et al. (1996). It seems probable that intermediate-mass stars that generally are prevented from becoming C stars by HBB may provide most of the nitrogen. We note that Brett (1991), in his analysis of luminous AGB stars in the SMC, finds strong CN bands, indicating C to N conversion by HBB.

2.5. FLUORINE

The galactic production of the single stable isotope of flourine, ^{19}F, has been a matter of discussion and is still rather unclear. Jorissen et al. (1992) identified lines of HF in the 2 micron region for K, M, S and N giants and derived F abundances. They found that the F/O ratio in AGB stars increases with C/O, with maximum values for stars with C/O ratios not too much in excess of 1 (SC stars). Their result seems to imply that the thermal pulses produce fluorine, and they (cf. also Forestini et al. 1992) suggest as the most probable scenario that ^{13}C(α,n)^{16}O reactions produce neutrons, some of which are captured by ^{14}N to produce ^{14}C and protons, which in turn are captured by ^{18}O: ^{18}O(p,α)^{15}N(α,γ)^{19}F. The flourine is then brought to the surface by convection following the thermal pulse. This scenario is complicated by several circumstances, e.g. the new higher rate for the reaction ^{18}O(α,γ)^{22}Ne which may deplete ^{18}O enough to decrease the significance of the second part of the reaction chain (cf. Frost & Lattanzio 1996). In any case, the over-abundances of F found in SC and N stars by Jorissen et al. (1992), ranging from 3 to 30 times the solar values, indicate that these stars may well be major contributors to the galactic flourine; an alternative is production in SNII (Woosley et al. 1990; Timmes et al. 1995).

An interesting way of clarifying this issue further may be to determine the flourine abundances in less evolved M stars with different metal abundances, since different scalings of, say, [F/O] with [Fe/H] may be expected for the different production sites.

2.6. NEON

The dominant neon isotope in the solar system, ^{20}Ne, is probably mainly produced by SNeII (cf. Woosley & Weaver 1995; Timmes et al. 1995). The SNe yields of ^{22}Ne are about one order of magnitude lower than those of ^{20}Ne which is consistent with the isotopic ratios observed in the solar system. However, ^{22}Ne may be formed at thermal pulses in AGB stars in the convective intershell through α-capture on ^{14}N, which after β-decay leads to ^{18}O(α,γ)^{22}Ne (Boothroyd & Sackman 1988; Gallino et al. 1990). In the AGB model calculations of Marigo et al. (1996), considerable amounts of ^{22}Ne are produced and ejected, in particular for models with masses around 2.5 $M_\odot$ which get most carbon rich. The predicted ^{22}Ne yields are fairly independent of metallicity (though higher for Z=0.008 than for Z=0.02), and so high that the AGB stars are suggested to be a major contributor of galactic ^{22}Ne. In particular, the envelopes of C stars are predicted to have a ^{20}Ne/^{22}Ne ratio considerably less than 1, even close to 0.1.

The Ne enrichment expected in C-rich PNe according to these results was not traced in the sample of southern PNe studied by Kingsburgh &

Barlow (1994), nor can it be seen in the sample of PNe from the Magellanic Clouds studied by Leisy & Dennefeld (1996). However, Corradi & Schwarz (1995) found a sample of bipolar PNe to be enriched in Ne and Marigo et al. (1996) suggest that the build-up of ^{22}Ne could be the reason for this. We note that Lewis et al. (1990) and Nichols et al. (1993) find consistently low isotopic ratios in gas-rich meteoritic SiC grains.

2.7. SODIUM AND ALUMINUM

Na and Al are, as well as Mg, generally identified as products of Ne and C burning in massive stars while the production in SNeIa is probably small (Nomoto et al. 1992). The synthesis of Na and Al is controlled by the neutron flux during Ne and C burning which in turn is dependent on the initial metallicity and primarily on the initial O abundance (^{16}O being converted to ^{22}Ne, via ^{14}N, in He-burning and the extra neutrons in ^{22}Ne, when being liberated, are essential to the formation of Na and Al). Therefore, one expects a rapid increase of Na/Mg ratios with Fe/H, and such a tendency is also apparent in the calculations of Timmes et al. (1995). For the most metal-rich solar-type stars the positive correlation between Na/Mg and Fe/H is well established (Feltzing & Gustafsson 1998). However, the observations of disk stars by Edvardsson et al. (1993), as well as observations of halo stars, do not show this tendency very clearly (Timmes et al. 1995). Edvardsson et al. find a tendency for the abundance ratio of Na/Mg to be smaller in the inner Galaxy than in the outer, at a given Mg/H, for disk-stars more metal-poor than the Sun. This suggests that Na and Mg, respectively, were formed in stars of different types. Thus, there might be additional sources of sodium and possibly of aluminum.

There is some additional evidence that intermediate-mass stars or even low-mass stars might contribute in these respects. In intermediate-mass stars sodium may be synthesized in the hydrogen-burning shell through the neon-sodium cycle, and by proton captures on ^{22}Ne (Denisenkov 1989; Denisenkov & Denisenkova 1990; Langer et al. 1993). On longer time-scales, i.e. smaller masses, proton capture on ^{20}Ne may also be significant, and the results may be brought to the surface if efficient mixing is at hand. Observationally, yellow field supergiants appear sodium rich (Boyarchuk & Lyubimkov 1985) but they hardly contribute significantly to the galactic Na. A fraction of low mass red giants in globular clusters show enhanced Na and Al and are correspondingly poor in O (Norris & Da Costa 1995 and references given therein). Recently Cavallo et al. (1996) have attempted to model this, by following the nucleosynthesis in low-mass red giant model sequences, and they find substantial Na-enrichments in the region above the hydrogen-burning shell throughout the giant branch, independent of metallicity. For the lowest metallicities Al is also produced. With suitable mixing processes these elements will be visible on the surface and may even, after mass loss, contribute to the global enrichment of the Galaxy.

There is, however, no strong argument for this low-mass star production of Na and Al to be linked to the existence of C stars. Conversely, the meager abundance analyses that exist do not support such a hypothesis; e.g. Lambert et al. (1986) find normal Na/Ca ratios on the basis of 1 line for each element in the 2 μm region.

There is an interesting possibility that AGB stars contribute radioactive ^{26}Al (Kudryashov & Tutukov 1988), decaying to ^{26}Mg with emission of 1809 keV photons, detected in space. Guélin et al. (1995) have recently found some evidence for ^{26}AlF millimeter emission from the carbon-rich envelope of IRC +10216. Huss & Wasserburg (1996) comment on the finding of high ^{26}Al/^{27}Al ratios in some SiC grains. The high temperatures needed to produce ^{26}Al suggest rather high mass stars as sites if HBB is invoked. This is, however, not easily reconciled with other isotopic ratios.

2.8. THE *s*-ELEMENTS

The early discovery by Merrill (1952) of the unstable element technetium in S stars was a clear indication that these stars could be a source of the *s*-process elements in general (see also Cameron 1955). AGB stars are now generally found to be more or less *s*-element rich. C stars are believed to be the most enriched (see below).

Lambert (1992) gives several arguments in favor of the idea that *s*-elements are produced in AGB stars of low mass ($\lesssim 3\,M_\odot$) rather than in stars of intermediate mass. In intermediate-mass AGB stars, the temperature in the He-burning shell is high enough to ignite the ^{22}Ne(α,n)^{25}Mg neutron source. That would lead to an excess abundance of ^{25}Mg (cf. Lambert 1991, and references therein). Smith & Lambert (1986) found no ^{25}Mg enhancement in their seven randomly selected *s*-element enriched stars, which suggests that these were all low-mass AGB stars. In these stars the ^{13}C(α,n)^{16}O reaction is the probable neutron source.

The neutron density at the *s*-process site can be determined from observations of isotope abundances at certain branching points of the *s*-path in the chart of nuclides. Two useful branching points are the ones at ^{95}Zr and ^{85}Kr. Lambert et al. (1995) found no evidence of ^{96}Zr in ZrO bands in S star spectra, implying a neutron density of less than 5×10^8 cm^{-3}, much less than what is expected in regions where the ^{22}Ne neutron source operates. This again suggests that intermediate-mass AGB stars are not the major contributors of *s*-processed elements in our Galaxy.

Until recently, it was believed that the ^{13}C neutron source was in operation during the thermal pulses of low-mass stars. Straniero et al. (1995) have, however, found from an evolutionary model sequence (for 3 $M_\odot$) that the ^{13}C neutron source is activated during the intervals *between* the thermal pulses. This suggests a lower neutron density (10^7 cm^{-3}), and that the ^{13}C is consumed during the interpulse period. Semiconvection is essential for the *s*-process (see Sackmann & Boothroyd 1991, and references therein); this will allow mixing of protons into the carbon pocket of the thermal pulses leading to fresh ^{13}C. Predictions from the models of Straniero et al. regarding one of the signatures of the low neutron density, the Rb/Sr ratio which depends on the *s*-path at the ^{85}Kr branch, are in agreement with recent observations of MS and S stars by Lambert et al. (1995).

Mean neutron exposures deduced from observations of 34 MS and S stars by Smith et al. (1987) suggest that the solar system *s*-element distribution could arise from a mixture of MS, S and C stars which return *s*-element enriched material to the ISM. Their *s*-element excesses are for MS stars a factor of 2–3, for S stars 4–6 and for C stars 5–10. Note that the latter abundances are based on the uncertain abundance analysis of the crowded visual spectra by Utsumi (1985). These figures, in combination with estimated total mass loss, are high enough to explain the *s*-element abundance in the solar system. Also, Parthasarathy (1996) found *s*-element enhancement relative to the Sun of 2–40 for some post–AGB stars.

There is also other more indirect, though strong, empirical evidence for the *s*-elements being formed mainly in low-mass AGB stars. Edvardsson et al. (1993) showed, from studies of the composition of solar-type disk stars of different ages, that the major contributors to the enrichment of *s*-elements in the disk are stars with characteristic evolutionary times $> 3\times 10^9$ years, i.e. low-mass stars. This is significantly longer than the time scale of the iron production from SNeIa. The low-mass contribution to the *s*-elements in the galactic disk is also verified by Pagel & Tautvaišienė (1997). Moreover, from abundances in the halo they also trace a contribution of unknown origin but with a time scale characteristic of stars of $\sim 8\,M_\odot$.

The third dredge-up may be even more significant for populations with lower metallicity than solar (cf. Wood 1981) and provide strong *s*-element enrichment. We note that Kipper et al. (1996) found three presumably intrinsic C stars of Pop. II to have *s*-element enhancements of 1–3 dex.

We conclude that mass loss from precursors of C-rich PNe are most probably a main source of the *s*-elements in galaxies.

3. Conclusions

It seems most probable that the AGB stars in general, and C stars in particular, are the main contributors of *s*-elements; probable that their contributions of flourine and carbon are quite significant; and possible that their contributions of lithium (from the super Li-rich C stars), of ^{13}C (from J stars) and of Ne (i.e. ^{22}Ne) are of some importance. However, all of these statements are more or less uncertain, and the uncertainty is also great concerning the role of intermediate and low mass stars in the production of N, Na and Al. This is because a number of relatively fundamental questions concerning C stars still remain unanswered. In order to improve the situation new and more detailed and reliable abundance analyses for C stars and PNe are needed (also in nearby galaxies with different metallicities), as well as better models of nucleosynthesis and dredge-up in AGB stars. We also need to know more about mass loss — how much matter the stars eject, as a function of initial mass and composition, as well as when the stars lose mass relative to the time when their envelope enrichment occurs. Further studies of abundances in less evolved stars of different stellar populations are also of great significance. As regards the nucleosynthesis of two of the most important elements, carbon and nitrogen, more work on stars more massive than normal C stars seems also important.

The situation reminds us of one of the stories about the famous Nasrettin Hoca of Konya, a place not very far from Antalya. Nasrettin saw ducks on the lake shore and, thinking of his dinner, tried to catch one but it jumped into the lake and swam out of reach. The next one did the same. After several attempts he took a spoon and sat down at the shore and started eating water. Some friends passed by and asked him what he was doing. He answered: “I am having duck soup.”

We have tried to “catch” the evasive secrets of the C stars with different, more or less sophisticated methods. However, in spite of much progress presented at this meeting, the solutions of the problems seem to be at some distance. This partly reflects the experience, so common in science, that phenomena tend to become more complex when studied. In any case, more systematic investigations are now needed. If we undertake them, it seems that we shall get the most important answers long before Nasrettin Hoca has been able to walk to the center of his lake and catch his ducks.

John Lattanzio, Bernard Pagel, Lee-Anne Willson and Bob Wing are thanked for valuable suggestions, and Martin Asplund and Kjell Eriksson for comments on the manuscript.

References

Abia, C., Boffin, H. M. J., Isern, J. & Rebolo, R. 1993a, *A&A*, 272, 455
Abia, C. & Isern, J. 1996, *ApJ*, 460, 443
Abia, C., Isern, J. & Canal, R. 1993b, *A&A*, 275, 96
Andersson, H. & Edvardsson, B. 1994, *A&A*, 290, 590
Bessell, M. S., Wood, P. R. & Lloyd Evans, T. 1983, *MNRAS*, 202, 59

Blöcker, T. 1995, *A&A*, 297, 727

Boesgaard, A., Eriksson, K. & Gustafsson, B. 1996, in prep.

Boothroyd, A. I. & Sackmann, I.-J. 1988, *ApJ*, 328, 653

Boothroyd, A. I., Sackmann, I.-J. & Ahern, S. C. 1993, *ApJ*, 416, 762

Bowen, G. H. & Willson, L. A. 1991, *ApJ*, 375, L53

Boyarchuk, A. A. & Lyubimkov, L. S. 1985, *Bull. Crimean Astrophys. Obs.*, 66, 119

Brett, J. M. 1991, *MNRAS*, 249, 538

Brewer, J. P. 1996, *PASP*, 108, 379

Brown, L. E. 1992, *ApJ*, 389, 251

Cameron, A. G. W. 1955, *ApJ*, 121, 144

Cameron, A. G. W. & Fowler, W. A. 1971, *ApJ*, 164, 111

Cavallo, R. M., Sweigart, A. V. & Bell, R. A. 1996, *ApJ*, 464, L79

Claussen, M. J., Kleinmann, S. G., Joyce, R. R. & Jura, M. 1987, *ApJ Supp.*, 65, 385

Corradi, R. L. M. & Schwarz, H. E. 1995, *A&A*, 293, 871

Denisenkov, P. A. 1989, *Soviet Astr. Lett.*, 14, 435

Denisenkov, P. A. & Denisenkova, S. N. 1990, *Soviet Astr. Lett.*, 16, 275

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E. & Tomkin, J. 1993, *A&A*, 275, 101

Feltzing, S. & Gustafsson, B. 1998, *A&A Supp.*, 129, 237

Forestini, M., Goriely, S., Jorissen, A. & Arnould, M. 1992, *A&A*, 261, 157

Frost, C. A. & Lattanzio, J. C. 1996, in the 32^{nd} Liège Inst. Astrophys. Coll.: *Stellar Evolution: What should be done?*, ed. A. Noels et al., p. 307

Gallino, R., Busso, M., Picchio, G. & Raiteri, C. M. 1990, *Nature*, 348, 298

Garnett, D. R., Skillman, E. D., Dufour, R. J., Peimbert, M., Torres-Peimbert, S., Terlevich, R., Terlevich, E. & Shields, G. A. 1995, *ApJ*, 443, 64

Groenewegen, M. A. T. & de Jong, T. 1993, *A&A*, 267, 410

Groenewegen, M. A. T., van den Hoek, L. B. & de Jong, T. 1995, *A&A*, 293, 381

Guélin, M., Forestini, M., Valiron, P., Ziurys, L. M., Anderson, M. A., Chernicharo, J. & Kahane, C. 1995, *A&A*, 297, 183

Huss, G. R. & Wasserburg, G. J. 1996, *Lun. Planetary Sci.*, 27, 573

Jorissen, A., Smith, V. V. & Lambert, D. L. 1992, *A&A*, 261, 164

Jura, M. & Kleinmann, S. G. 1989, *ApJ*, 341, 359

Kahane, C., Cernicharo, J., Gómez-González, J. and Guélin, M. 1992, *A&A*, 256, 235

Kingsburgh, R. L. & Barlow, M. J. 1994, *MNRAS*, 271, 257

Kipper, T., Jørgensen, U. G., Klochkova, V. G. & Panchuk, V. E. 1996, *A&A*, 306, 489

Kudryashov, A. S. & Tutukov, A. 1988, *Astron. Zirk.*, 1525, 11

Lambert, D. L. 1991, in IAU Symp. 145: *Evolution of Stars: the Photospheric Abundance Connection*, ed. G. Michaud and A. Tutukov (Kluwer), p. 299

Lambert, D. L. 1992, in the 31^{st} Herstmonceux Conf.: *Elements and the Cosmos*, ed. M. G. Edmunds and R. Terlevich (Cambridge Univ. Press), p. 92

Lambert, D. L., Gustafsson, B., Eriksson, K. & Hinkle, K. H. 1986, *ApJ Supp.*, 62, 373

Lambert, D. L., Smith, V. V., Busso, M., Gallino, R. & Straniero, O. 1995, *ApJ*, 450, 302

Langer, G. E., Hoffman, R. & Sneden, C. 1993, *PASP*, 105, 301

Leisy, P. & Dennefeld, M. 1996, *A&A Supp.*, 116, 95

Lewis, R. S., Amari, S. & Anders, E. 1990, *Nature*, 348, 293

Maeder, A. 1992, *A&A*, 264, 105

Marigo, P., Bressan, A. & Chiosi, C. 1996, *A&A*, 313, 545

Matteucci, F., D'Antona, F. & Timmes, F. X. 1995, *A&A*, 303, 460

McKellar, A. 1940, *PASP*, 52, 407

Merrill, P. W. 1952, *ApJ*, 116, 21

Nichols, R. H. Jr., Amari, S., Hohenberg, C. M., Hoppe, P. & Lewis, R. S. 1993, *Meteoritics*, 28, 410

Nomoto, K., Tsujimoto, T., Yamaoka, H., Kumagai, S. & Shigeyama, T. 1992, in the 31^{st} Herstmonceux Conf.: *Elements and the Cosmos*, ed. M. G. Edmunds and R. Terlevich (Cambridge Univ. Press), p. 55

Norris, J.E. & Da Costa, G.S. 1995, *ApJ*, 441, L81
Ohnaka, K. & Tsuji, T. 1996, *A&A*, 310, 933
Olofsson, H., Bergman, P., Eriksson, K. & Gustafsson, B. 1996, *A&A*, 311, 587
Olofsson, H., Eriksson, K., Gustafsson, B. & Carlström, U. 1993a, *ApJ Supp.*, 87, 267
Olofsson, H., Eriksson, K., Gustafsson, B. & Carlström, U. 1993b, *ApJ Supp.*, 87, 305
Pagel, B.E.J. & Tautvaišienė, G. 1997, *MNRAS*, 288, 108
Parthasarathy, M. 1996, private communication
Pasquali, A. & Perinotto, M. 1993, *A&A*, 280, 581
Pettini, M., Lipman, K. & Hunstead, R.W. 1995, *ApJ*, 451, 100
Plez, B., Smith, V.V. & Lambert, D.L. 1993, *ApJ*, 418, 812
Pottasch, S.R. 1992, *Astron. Astrophys. Rev.*, 4, 215
Prantzos, N., Aubert, O. & Audouze, J. 1996, *A&A*, 309, 760
Prantzos, N., Vangioni-Flam, E. & Chauveau, S. 1994, *A&A*, 285, 132
Reeves, H., Richer, J., Sato, K. & Terasawa, N. 1990, *ApJ*, 355, 18
Renzini, A. & Fusi Pecci, F. 1988, *Ann. Rev. Astron. Astrophys.*, 26, 199
Renzini, A. & Voli, M. 1981, *A&A*, 94, 175
Richer, H.B. 1981, *ApJ*, 243, 744
Richer, H.B., Olander, N. & Westerlund, B.E. 1979, *ApJ*, 230, 724
Rola, C. & Strasińska, G. 1994, *A&A*, 282, 199
Sackmann, I.-J. & Boothroyd, A.I. 1991, in IAU Symp. 145: *Evolution of Stars: the Photospheric Abundance Connection*, ed. G. Michaud and A. Tutukov (Kluwer), p. 275
Sackmann, I.-J. & Boothroyd, A.I. 1992, *ApJ*, 392, L71
Sarmiento, A. & Peimbert, M. 1985, *Rev. Mex. Aston. Astrofís.*, 11, 73
Scalo, J.M. 1976, *ApJ*, 206, 795
Scalo, J.M. & Ulrich, R.K. 1973, *ApJ*, 183, 151
Smith, V.V. & Lambert, D.L. 1986, *ApJ*, 311, 843
Smith, V.V., Lambert, D.L. & McWilliam, A. 1987, *ApJ*, 320, 862
Spite, F. & Spite, M. 1982, *A&A*, 115, 357
Straniero, O., Gallino, R., Busso, M., Chieffi, A., Raiteri, C.M., Limongi, M. & Salaris, M. 1995, *ApJ*, 440, L85
Stürenburg, S. & Holweger, H. 1990, *A&A*, 237, 125
Thielemann, F.-K., Nomoto, K. & Hashimoto, M.-A. 1996, *ApJ*, 460, 408
Timmes, F.X., Woosley, S.E. & Weaver, T.A. 1995, *ApJ Supp.*, 98, 617
Tinsley, B.M. 1978, in IAU Symp. 76: *Planetary Nebulae*, ed. Y. Terzian (Reidel), p. 341
Tomkin, J., Lemke, M., Lambert, D.L. & Sneden, C. 1992, *AJ*, 104, 1568
Tomkin, J., Woolf, V.M., Lambert, D.L. & Lemke, M. 1995, *AJ*, 109, 2204
Utsumi, K. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P.C. Keenan (Reidel), p. 243
Vila-Costas, M.B. & Edmunds, M.G. 1993, *MNRAS*, 265, 199
Willson, L.A., Bowen, G.H. & Struck, C. 1996, in *From Stars to Galaxies*, ed. C. Leitherer, U. Fritze-von Alvensleben and J. Huchra, ASP Conf. Ser., 98, 197
Wood, P.R. 1981, in *Physical Processes in Red Giants*, ed. I. Iben Jr. and A. Renzini (Reidel), p. 135
Woosley, S.E., Hartmann, D.H., Hoffman, R.D. & Haxton, W.C. 1990, *ApJ*, 356, 272
Woosley, S.E. & Weaver, T.A. 1995, *ApJ Supp.*, 101, 181
Zuckerman, B. & Aller, L.H. 1986, *ApJ*, 301, 772