THE EARLY HISTORY OF OUR GALAXY: CHEMICAL EVOLUTION

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Abstract. A general review is given of chemical abundance determinations; particular emphasis is given to abundances of galactic and extragalactic metal-poor objects since presumably they represent the abundances of the primeval material from which our Galaxy was formed. The following results are stressed: (a) most of the helium present in the galaxies of the local group as well as in other galaxies was produced before these objects were formed, (b) the heavy elements were produced mainly as the result of stellar evolution, (c) there is a chemical abundance gradient in our Galaxy and, by analogy with other galaxies, it is expected to be steeper near the nucleus, (d) the carbon and oxygen content of our Galaxy increased at a rate different from the metals, reaching their present abundance earlier than the other heavy elements, and (e) the increase of the iron abundance in the disk of our Galaxy with time has been small while that of carbon is negligible; furthermore, as a group the super-metal-rich stars correspond to the old disk population. Several models of galactic chemical evolution are reviewed.

1. Introduction

It is not possible to cover all the research papers relevant to the chemical history of the Galaxy in a review of this nature, therefore I have been forced to be selective in the topics covered. I will not discuss the light elements, with the exception of hydrogen and helium. There are two recent review papers on the light elements by Reeves *et al.* (1973) and by Tinsley (1973). A very important element as regards its abundance is deuterium which, according to Hoyle and Fowler (1973) and Colgate (1973), can be produced not only in the big-bang but also by spallation in envelopes of super-massive objects or in supernovae. However, the energy required to produce the galactic deuterium by this method is very large and consequently it is more likely that this element has been produced in the big-bang. At the other end of the atomic mass range, the information that can be obtained from the radioactive elements is very limited and it will only be mentioned that from the ^{232}Th/^{238}U and the ^{235}U/^{238}U ratios found on Earth the formation of radioactive elements appears to have been more pronounced in the early stages of our Galaxy than later on (Schramm, 1972).

In Section 2 we review galactic abundance determinations relevant to the chemical evolution of our Galaxy, but discuss first some results obtained from other galaxies, which might bear on this problem. The latter offer two advantages over the local observations: firstly, we can observe galaxies in which star formation has not been very prominent so that their chemical abundances might be more representative of the original material from which galaxies were formed, and secondly we can observe at different distances from the centre and thus study possible chemical abundance gradients.

In Section 3 we will discuss recent theories on production sites and in Section 4 review models of the evolution of the Galaxy proposed to explain the observations.

John R. Shakeshaft (ed.), The Formation and Dynamics of Galaxies. 141–156. *All Rights Reserved.*

2. Observations

2.1. INTERSTELLAR MATTER IN EXTERNAL GALAXIES

2.1.1. H II *Regions and Nuclei of Galaxies*

In order to understand the evolution of the Galaxy one of the key elements to study is helium. An overall examination of the He/H ratio is thus essential. The most reliable determinations are those obtained from normal H II regions observed optically. Peimbert and Spinrad (1970a) derived very accurate N(He)/N(H) ratios in five extragalactic objects which yielded an average value of ~0.10. To obtain a value as close as possible to the primeval one it is clear that objects for which the contamination due to stellar evolution has been small should be studied. Therefore Peimbert and Spinrad (1970b) obtained the He/H ratio in NGC 6822, an irregular galaxy of the local group, slightly metal deficient. More relevant results were obtained by Searle and Sargent (1972), who determined the He/H abundance ratio in I Zw 18 and II Zw 40, two blue compact galaxies which are metal deficient, particularly the former, and by Dufour (1973) on the Magellanic clouds, especially interesting for the study of the chemical evolution of our Galaxy, since the three objects probably originated from material with the same primeval chemical composition. A summary of the abundances derived from metal poor H II regions is presented in Table I. It is clear from this table that the He/H abundance ratio is nearly the same for all objects and similar to that found in H II regions of the solar neighbourhood.

Another problem of interest that can be tackled is the presence of chemical abundance gradients across the disks of spiral galaxies. Peimbert (1968) argued that the nitrogen abundance in the nuclei of spiral galaxies was higher than that of H II regions of the solar neighbourhood. Searle (1971) established the existence of N/H and O/H abundance gradients across the disks of spiral galaxies; the former being steeper than

TABLE I

Abundances of extragalactic metal-poor gaseous nebulae[a]

	[He/H]	[O/H]	[N/O]	[Ne/O]	Reference
NGC 6822 V	−0.02	−0.23	−0.55		[1]
LMC	−0.03	−0.30	−0.45	0.00	[2]
NGC 5471	−0.01	−0.42		+0.17	[3]
II Zw 40	−0.03	−0.50		0.00	[3]
NGC 185-1	+0.15	−0.83			[4]
SMC	−0.02	−1.01	−0.39	−0.08	[2]
I Zw 18	+0.03	−1.14		−0.14	[3]

[a] The abundance ratios are logarithmic, relative to those of the Orion Nebula by Peimbert and Costero (1969).

[1] Peimbert and Spinrad (1970b).
[2] Dufour 1973.
[3] Searle and Sargent (1972)
[4] Jenner *et al.* (1973).

the latter. Benvenuti *et al.* (1973) established the presence of a N/S abundance gradient extending throughout the disks of spiral galaxies but more pronounced near the nuclei (see Table II). Independent evidence, based on stellar absorption features, in favour of the existence of abundance gradients close to and in the nuclei of galaxies has also been presented by McClure (1969), Spinrad *et al.* (1971), and Spinrad *et al.* (1972).

TABLE II

Chemical abundances[a] at different distances from galactic nuclei

Object	H	N	S	N/S
M51 (Nucleus $r \leqslant 1.25''$)				1.53
M81 (Nucleus $r \leqslant 1.25''$)				1.42
M51 (Nucleus $r \leqslant 3.5''$)				1.07
M81 (Nucleus $r \leqslant 3.5''$)				0.98
M33 (inner H II Regions)				0.48
M8	12.00	7.50	7.14	0.36
Orion	12.00	7.63	7.50	0.13
M101 (outermost H II Regions)				−0.35

[a] Given in $\log N$ (Benvenuti *et al.*, 1973).

2.1.2. *Planetary Nebulae*

Jenner *et al.* (1973) have obtained the relative hydrogen, helium and oxygen abundances in NGC 185-1, a planetary nebula in NGC 185, for which the O/H ratio is lower by about an order of magnitude, and the He/H ratio is similar to those of H II regions and planetary nebulae in our Galaxy.

Sanduleak *et al.* (1972) found that the 6584/Hα ratios in planetary nebulae (and probably also the H II regions) of the SMC are very small and they conclude that nitrogen must be deficient in the planetary nebulae. This is in agreement with the abundance determinations of Dufour (1973) and implies that the planetary nebulae in the SMC may be similar in their chemical composition to that in M15.

2.1.3. *Quasars*

It is well known that some quasars exhibit very faint helium emission lines that might imply an intrinsically low helium abundance (Osterbrock and Parker, 1966; Wampler, 1967, 1968; Bahcall and Kozlovsky, 1969a, b; Peimbert and Spinrad, 1970a). However, the derived He/H abundance ratios are strongly model dependent, so these abundance determinations are not reliable at present (Burbidge *et al.*, 1966; Williams, 1971; MacAlpine, 1972; Jura, 1973).

2.2. INTERSTELLAR MATTER IN OUR GALAXY

2.2.1. H II *Regions*

Some of the most reliable determinations of the He/H abundance ratios from optical emission lines have been made by Peimbert and Costero (1969). The objects observed are mainly H II regions of the solar neighbourhood, where interstellar reddening is small.

He/H abundance ratios have also been determined from radio observations for many H II regions at different distances from the centre of our Galaxy (see for example Churchwell and Mezger, 1970). The agreement between the radio and optical determinations for the objects in common is very good. It should be mentioned that there are three H II regions within 150 pc of the centre of our Galaxy where $N(He^{+}+He^{++})/N(H^{+})$ is less than 0.03 and thus considerably smaller than the N(He)/N(H) value determined in all the H II regions observed optically. Unfortunately, the radiation field is not known and it is not possible to estimate the amount of neutral helium inside these H II regions (Churchwell and Mezger, 1973; Huchtmeier and Batchelor, 1973). From the arguments presented in this review the helium abundances in these regions are expected to be normal. There are at least three possible explanations for the presence of large amounts of neutral helium inside these H II regions: (a) a luminosity function near the nucleus of our Galaxy different from that of the solar neighbourhood, in the sense that it does not contain stars of spectral type earlier than O9; (b) the existence of dust particles which absorb more efficiently those photons able to ionize helium than those able to ionize hydrogen; and (c) cloud collisions with relative velocities in the 30 to 60 km s^{-1} range such that hydrogen is ionized but not helium. At present there are arguments in favour of each of these hypotheses and it is not possible to decide among them.

The nitrogen, oxygen and sulphur abundances relative to hydrogen have been determined in H II regions of the solar neighbourhood and are very similar to the solar abundances (Peimbert and Costero, 1969; Goldberg *et al.*, 1960; Lambert, 1968; Lambert and Warner, 1968).

2.2.2. *Planetary Nebulae*

From a photoelectric study of planetary nebulae of the solar neighbourhood, Peimbert and Torres-Peimbert (1971) found that the He/H and the O/H abundance ratios were very similar to those of H II regions of the solar neighbourhood, while the N/O abundance ratio was found to be a factor of four higher. These two results are consistent with the ideas, firstly that the relative H, He and O abundances are representative of the matter from which planetary nebulae were formed and secondly that the envelopes of planetary nebulae enrich the N/H abundance ratio of the interstellar medium.

Two planetary nebulae of Population II have been studied in detail: 49+88°1 (Miller, 1969) and K648, a member of the globular cluster M15 (O'Dell *et al.*, 1964; Peimbert 1972). Both planetary nebulae show a He/H ratio similar to that of H II regions, while they are underabundant in oxygen and neon by a factor of about 10. The case of K648 is particularly interesting because the Fe deficiency derived from the globular cluster starlight is of about two orders of magnitude, and thus it appears that O and Ne are not correlated with the iron abundance. These results are presented in Table III.

TABLE III

Abundances of galactic objects[a]

	[He/H]	[O/H]	[N/O]	[Ne/O]	[S/O]	[A/O]	References
K 648 (M15)	0.00	−1.12	< −0.22	+0.17			[1]
49 + 88°1	+0.11	−0.78	+0.77	−0.27			[2]
Planetary Nebulae of the Solar Neighbourhood	+0.04	−0.03	+0.64	0.0			[3]
Novae	+0.18	+0.84	+1.23		−0.26		[4]
RS Ophiuchi	+0.63	+1.02	+0.75		−0.52		[5]
Cas A		> +1.64	< −1.44		+0.11	+0.05	[6]

[a] Relative to those of Orion Nebula by Peimbert and Costero (1969).

[1] Peimbert (1972).

[2] Miller (1969).

[3] Peimbert and Torres-Peimbert (1971).

[4] Pottasch (1959).

[5] Pottasch (1967).

[6] Peimbert (1971).

2.2.3. *Novae*

Since the distribution of galactic novae corresponds to that of Population II objects, it is important to find out whether or not their observed abundances are those of the original material from which they were formed. Pottasch (1959, 1967) has determined chemical abundances from emission lines originating in shells of novae. He found for six objects that $[O/H] \sim +1.0$ and $[N/H] \sim +2.0$ and, by comparing RS Oph with the solar corona, that $[Fe/H] \sim +0.6$. Pottasch pointed out that, since iron is not produced by the nova system itself, this was an argument against the production of the other overabundant elements by the nova during the course of its evolution; however, a considerable fraction of hydrogen in this object has been converted into helium with the consequence that hydrogen has been depleted relative to the other elements and the iron abundance might be normal, with the only enriched elements being He, N and O and possibly C.

Mustel (1971) and Arkhipova (1973) find from a study of absorption lines that in DQ Herc and HR Del most elements show normal abundances but CNO are overabundant, by about two orders of magnitude in the former case and about an order and a half in the latter.

From the previous discussion it follows that at present it is not possible to derive the primordial abundances of these objects and that at least the observed H, He, C, N and O abundances have been affected by stellar evolution.

2.2.4. *Supernova Remnants*

The hypothesis that heavy-element enrichment of the interstellar medium is largely due to exploding supernovae can be tested by studying the chemical composition of supernova remnants. Observations of the Crab Nebula (Woltjer, 1958) show that, under the assumption of case *B* for the hydrogen lines, helium is overabundant by a factor of at least 2. However, the hydrogen lines might be closer to case *A* than to case *B* and consequently the helium overabundance might not be as large. The remnant of Cas A is more interesting because the velocity of expansion is considerably higher; it has been found that, in the system of fast moving knots, oxygen, sulphur and argon are overabundant by at least a factor of 30 with respect to hydrogen and nitrogen (Peimbert and van den Bergh, 1971; Peimbert, 1971).

2.3. STARS AND STELLAR SYSTEMS IN OUR GALAXY

2.3.1. *Metal Poor Stars*

Although Bw and sdB stars show very weak helium lines corresponding to low photospheric helium to hydrogen abundance ratios, various arguments suggest that these results are not reliable indicators of their internal composition and we therefore cannot use these objects to obtain information about their original He/H abundance ratios (Baschek *et al.*, 1972).

Some early results on the abundance of the elements from carbon to iron in metal-poor stars indicated that within a factor of two the relative abundances of the heavy elements were similar to those of the Sun even if their Fe/H ratio differed by as much as three orders of magnitude. However, recent and more accurate results imply that the situation is more complicated.

Wallerstein (1962) in a study of 31 G dwarfs found that manganese is deficient with respect to the other iron peak elements: chromium, nickel and iron. He also found that the stars having large velocities with respect to the local standard of rest are metal-poor but apparently α-rich with respect of iron, i.e. they show excesses of Mg, Si, Ca and Ti. Similar results were also presented by Spite (1968).

In a recent discussion on the chemical evolution of the Galaxy, Wallerstein (1971) reviewed the evidence in favour of the $[\alpha/\text{Fe}]$ enrichment in metal-poor stars and showed that sodium and aluminum did not increase in abundance until [Fe/H] reached -2.0 but subsequently increased rapidly to a total similar to that of iron. Since explosive carbon burning yields nuclei from neon through aluminum, Wallerstein suggests that this sudden increase in the sodium and aluminum abundances is due to a relatively higher efficiency of explosive carbon burning possibly caused by a higher initial abundance of CNO elements.

Hearnshaw (1972a, 1972b) analyzed 19 disk G subgiants, older or nearly as old as NGC 188. His results on Mg, Ca and Ti, as well as those on Mn, confirm the results by Wallerstein (1962). Furthermore the iron-deficient (disk) stars are generally no more than marginally carbon deficient, a result which should be compared with those of Cohen and Strom (1968) and Pagel and Powell (1966) who obtained $[\text{C/Fe}]=0.0$ and -0.1 for the two extremely metal-poor subdwarfs HD 140283 and HD 25329. The relationships found by Hearnshaw are presented in Table IV.

From a study of seventy G and K stars, mostly giants, Conti *et al.* (1967) concluded that the oxygen content of our galaxy increased at a rate different from that of the metals, reaching its present abundance sooner than the other heavy elements. The

TABLE IV

Results from 19 old subgiants[a]

Element	d[M/Fe]/d[Fe/H]
C	−0.7
Ca, Ti	−0.3
Fe, Cr, Ni	0.0
Mn	+0.8

[a] Hearnshaw (1972).

extremely metal-poor giant star HD 122563 (Wallerstein *et al.*, 1963; Pagel, 1965; Wolffram, 1972) has been recently studied to obtain the CN (Sneden, 1973) and O (Lambert *et al.*, 1974) abundances with the results [C/Fe] = −0.4; [N/Fe] = +1.2 and [O/Fe] = +0.6. These values indicate that probably some carbon was transformed into nitrogen through nuclear reactions in the stellar interior and that subsequently the material was brought up to the surface; the oxygen overabundance, however, could very well be primeval and supports the results of Conti *et al.* (1967) that the oxygen content increased earlier than the iron content of our galaxy.

Powell (1972) obtained the iron to hydrogen ratios of 93 late F dwarfs within 25 pc of the Sun from their ultraviolet excesses. The ages of these stars have been estimated from their positions in the H-R diagram. This study and that of Hearnshaw (1972a, 1972b) indicate that there has been a modest enrichment of Fe in the disk since the formation of the Galaxy, the average increase being by a factor of 4 and the scatter at any one age covering a range of a factor of 2 to 3. This result is in contradiction with the work of Bond (1970) who, from the study of 69 metal-poor stars of the solar neighbourhood, finds that for stars with $[\mathrm{Fe/H}] \gtrsim -1$ there is little or no correlation between galactic orbital eccentricity and chemical composition. Moreover, Hearnshaw does not find any significant increase in the carbon abundance which is a more representative element of the total Z value.

In an excellent review paper on population effects in the Galaxy (Pagel, 1972; see also Pagel, 1970), it is suggested that for halo stars in our Galaxy a correlation of the type [N/Fe] = [Fe/H] exists. This correlation is based on Gmb 1830, ν Ind, μ Cas and HD 6833. Tomkin (1972) also finds for Gmb 1830 that $[\mathrm{Fe/H}] \sim -1.3$ while $[\mathrm{N/H}] \sim -2.0$.

2.3.2. *Super-Metal-Rich Stars*

Torres-Peimbert and Spinrad (1971), from the chemical abundance determinations by Spinrad and Taylor (1969) and the theoretical evolutionary models by Torres-Peimbert (1971a), found that the mean age of nine SMR K giants is 6×10^9 yr and is larger than those of the old galactic clusters M67 and NGC 188 (Torres-Peimbert, 1971b). Torres-Peimbert and Spinrad were the first to point out that SMR stars as a group correspond to the old disk population. Hearnshaw (1972a, b) also finds that SMR stars are relatively old and that they do not represent the tail-end of the abundance distribution in young disk stars. A similar result is obtained by Williams (1972) from ages and kinematical properties of SMR stars. He finds that they are associated with the metal-poor stars having [Fe/H]~ -0.5 which suggests that the interstellar medium was poorly mixed during and immediately after the collapse of the Galaxy.

Janes and McClure (1972), from CN observations in 799 K giant stars, present evidence for a radial gradient in CN strength. This feature is correlated with [Fe/H] and implies an increase of [Fe/H]~ 0.23 between 15 and 5 kpc, from which they conclude that the heavy element abundance depends more on the position at birth of the star in the galactic disk than on its age. A similar result is obtained by Grenon (1972) who finds that SMR stars are old, have elliptical orbits and were probably born at a location closer to the galactic centre than their present position.

2.3.3. *Globular Clusters*

Van den Bergh (1965, 1967) and Sandage and Wildey (1967) suggested that there are at least two parameters affecting the characteristics of the horizontal branch in the HR diagram of globular clusters. The parameters most often considered have been the He/H abundance ratio and the Z value represented by the Fe abundance. The use of age as an independent parameter seems to be in contradiction with the idea that the globular clusters were formed during the rapid collapse phase of the galaxy and with the estimated duration of 2×10^8 yr for such a collapse (Eggen *et al.*, 1962). However, the recent findings that N(He)/N(H)$\sim$0.10 in the interstellar matter of several galaxies with widely different metal abundances have led several authors to search for other parameters to replace Y.

Rood (1972) has studied this problem and suggests that anomalous C-M diagrams in our Galaxy and in other galaxies could be explained by variations in age of the order of 1×10^9 yr; according to him, a further parameter could be the mass loss between the red giant phase and the horizontal branch. Hartwick and McClure (1972), from CN observations of red giant stars in globular clusters, have suggested that, in addition to Fe/H, a second independent parameter could be the nitrogen abundance.

In Table V we show some CNO abundances derived from different objects, and it is clear from this table as well as from the discussion in this section that for many objects there is no good correlation between the Fe and the CNO abundances Furthermore Simoda and Iben (1968, 1970) have demonstrated the importance of CNO abundances (particularly that of oxygen) in the evolution of population II stars; since most of the Z value is due to CNO elements and not to the Fe group, it follows that for studies of galactic and stellar evolution it is very important to know the CNO abundances. Consequently it is indeed quite possible that a second parameter to explain the HR diagrams of globular clusters is the CNO abundance.

3. Theoretical Production of Chemical Elements

3.1. BIG BANG

All the well-studied H II regions in our Galaxy and in other galaxies point to

TABLE V

CNO abundances[a]

	[Fe/H]	[C/H]	[N/H]	[O/H]	References
HD 122563	−2.7	−3.1	−1.5	−2.1	[1, 2, 3]
HD 140283	−2.2	−2.2			[4]
K 648 (M15)	−2.1		< -1.34	−1.12	[5]
HD 25329	−1.3	−1.4	−0.8		[6]
ν Indi	−1.2		−1.9		[7]
Gmb 1830	−1.1		−2.0		[7, 8]

[a] Relative to the solar ones.
[1] Wolffram (1972).
[2] Sneden (1973).
[3] Lambert *et al.* (1974).
[4] Cohen and Strom (1968).
[5] Peimbert (1972).
[6] Pagel and Powell (1966).
[7] Pagel (1972).
[8] Tomkin (1972).

$N(He)/N(H)=0.10\pm0.02$ and there is at present no clearcut observation that implies a considerably lower or higher primeval helium abundance for any object. Therefore the helium abundance in galaxies and in particular in ours should be the result of a very general process. Calculations of nucleosynthetic processes (Wagoner *et al.*, 1967) suggest that a simple version of the big bang provides the best explanation. These computations also show that, for the range of baryonic density comparable with observations, the big bang can be responsible only for the abundances of D, ^{3}He, ^{4}He, and possibly ^{7}Li in our Galaxy and not for the cosmic abundances of the rest of the elements.

3.2. SUPERMASSIVE OBJECTS

To explain the energy requirement of strong radio sources Hoyle and Fowler (1963a, b) proposed the existence of supermassive objects (SMO) with masses in the range 10^5 to 10^8 $M_\odot$ which release energy by violent explosions from galactic nuclei. It was suggested, moreover, that these objects could also produce the helium and metal abundances observed in extreme Population II stars.

Wagoner *et al.* (1967) made several models of SMO whose gravitational collapse is reversed at some specified temperature They found that in the more realistic cases where protons were initially present the computations predicted similar abundances for C^{12} and C^{13} but these particular models are ruled out by the value $C^{12}/C^{13}>3$ determined for eight extremely metal-poor stars by Cohen and Grasdalen (1968).

Bisnovatyi-Kogan (1968) studied exploding supermassive stars in the 10^5 $M_\odot$ range and, in the only interesting cases, most of the hydrogen was converted into helium. Moreover, Wagoner (1969) computed the element production in SMO for expansion rates of the order of 10^4 to 10^7 times the gravitational expansion. Regardless of the physical plausibility of these expansion rates, there is no observational evidence for massive gaseous clouds with a very high He/H ratio, hence apparently ruling out such models. There are available several recent computations of SMO, but in most cases there are no detailed evolutionary models and Population I abundances have been assumed.

Silk and Siluk (1972) have suggested that the primordial gas out of which the Galaxy condensed may have been significantly enriched in heavy elements by material ejected from quasi-stellar objects, the assumption being that these heavy elements would be formed in SMO. The observational objections mentioned above would seem to rule out this theory also. In a modified theory, in which the heavy elements in quasars are produced by normal stars, we would still be faced with the problem of the time scale for element formation and the practically unknown chemical abundances and rates of mass ejection from quasars.

To summarize, it appears that SMO are not responsible for the helium and metal abundances observed in Population II stars.

3.3. Normal stars

Burbidge *et al.* (1957) proposed that the synthesis of the elements takes place in stars. According to them, the galaxy condensed from a cloud of hydrogen and the heavier elements were produced in several generations of stars that were formed, evolved and later spread part of the processed matter into the interstellar medium.

It has been predicted from stellar evolution models (Iben, 1964, 1967) that nitrogen is enriched through the CN cycle and convected to the surface when the stars leave the main sequence and travel to the giant branch; furthermore Paczynski (1970) has suggested that stars less massive than about $4M_\odot$ lose only the material above the hydrogen-burning shell. The nitrogen enrichment effect has been confirmed observationally in the envelopes of planetary nebulae. These objects seem to provide a large fraction of the nitrogen enrichment of the interstellar medium and may be partly responsible for the nitrogen gradient observed across the disks of spiral galaxies (Torres-Peimbert and Peimbert, 1971). Both planetary nebulae and mass loss from red giants will only affect appreciably the carbon and nitrogen abundances of the interstellar medium.

Detailed calculations of explosive nucleosynthesis (Arnett, 1969; Truran and Arnett, 1970; Arnett *et al.*, 1971) have indicated that the material expelled in the detonation events which give rise to supernovae will typically be composed of elements from carbon to iron. Furthermore Arnett (1971) obtains an excellent agreement between the theoretical predictions and the solar abundances. These results strongly suggest that the chemical enrichment of our Galaxy is mainly produced by stars.

The apparent different pace of enrichment of CO and the elements of the iron group can be explained if the efficiency of helium burning followed by mass loss, relative to explosive silicon burning, was higher in the early generations of stars than in the later ones. This could be due to less massive supernovae and/or to a lack of seed elements for the onset of silicon burning in the early stages of galactic evolution.

4. Models of Galactic Chemical Evolution

From the frequency with which main sequence stars of different metal abundance occur in the disk, van den Bergh (1962) pointed out that the rate of metal creation in the Galaxy has decreased much faster than the rate of star formation. A result similar to van den Bergh's was obtained independently by Schmidt (1963) who noted that, under the assumption of a constant initial mass function (IMF), it was not possible to explain the lack of metal-poor stars in the solar neighbourhood; he therefore postulated that the IMF initially contained more massive stars than it does now. This scarcity of metal-poor stars in the disk has been the key issue in all the ideas and models both in favour of and against the chemical evolution of the Galaxy.

A more elaborate model based on the three basic assumptions made by Schmidt (1963, namely: no mass infall in the disk from the halo or from the intergalactic medium, an IMF containing more massive stars than at present, and a homogeneous collapse) was developed by Truran and Cameron (1971) who suggested that in the early halo nearly all the stars produced were more massive than 5 $M_\odot$. They were able to explain the lack of metal-poor stars in the disk of the Galaxy, and in their model the metal abundance increases monotonically with time.

Talbot and Arnett (1971), on the assumption of a constant IMF and no mass infall, have produced models in which the metal abundance of the interstellar medium initially increases with time but can decrease later or level off to an asymptotic value.

On the basis of the proposed interpretation by Oort (1970) of the 21-cm observations of high-velocity clouds in our Galaxy, Larson (1972a, b) has considered mass infall from the intergalactic medium to galaxies and its effect on galactic evolution. He suggests that during the later stages in the formation of galaxies there is approximate equilibrium between the rate of infall of gas and the rate at which gas is transformed into stars, so that the amount of interstellar matter in the Galaxy remains approximately constant with time. On this assumption he finds that the chemical composition of the disk is almost independent of time and of any initial element synthesis in the Galaxy, a result which may account for the observed fact that to a first approximation the heavy element abundance, Z, in the solar neighbourhood seems to be almost constant as a function of time. A higher proportion of massive stars would then be needed towards the nuclei of galaxies to explain the observed abundance gradients.

Quirk and Tinsley (1973) have assumed that stars are formed very efficiently until the gas content reaches equilibrium at its present value (10^9 yr), and thereafter the birthrate just equals the rate at which gas enters the system from stellar mass-loss or from infall of intergalactic matter. They propose a time variation of the IMF, with a higher proportion of massive stars in the past than at present. The models predict an initial increase of metallicity of the interstellar gas with time, followed by a later decline as the infalling primeval material dilutes the initial enrichment.

The hypothesis that the IMF contained more massive stars when the Galaxy was formed has been recently under attack. Van den Bergh (1972) pointed out that the luminosity function of disk stars suggests that the stellar birthrate function initially contained relatively *more* stars of low mass than it does now. Moreover, from the results of Woolley *et al.* (1971) for the luminosity function of stars within 25 pc of the Sun, Unsöld (1972) finds that the luminosity function of the unevolved stars is the same for the disk and the halo, from which he concludes that it is highly improbable that the halo IMF had originally a very large peak for stars with 5 to 10 times larger masses. Unsöld (1969, 1972) has used this argument, together with the observed uniformity of the relative abundances of the heavier elements, to support his theory that there has not been appreciable chemical evolution in our Galaxy due to individual stars and that the heavier elements originated in a gigantic explosion at a very early stage of evolution of the galactic nucleus.

From the near uniformity of the chemical composition in the interstellar gas of Sb and Sc galaxies, Searle (1972) also argues that it is unlikely that the IMF was very different from the present one in the early stages of evolution of our Galaxy. He has suggested that the IMF is the same everywhere and at all times, and explains the observed low fraction of metal-deficient stars in the disk by proposing that, contrary to Schmidt's (1963) hypothesis, *the collapse of the galaxy was inhomogeneous*, with enhanced star formation in the regions of high metal content. From ratios of stellar mass to gas mass of 1 to 100 in Sb and Sc galaxies, he predicts the present day metal-to-hydrogen ratio in the interstellar medium to be within the narrow limits $0.4\,Z_{\odot} \leqslant Z \leqslant \leqslant 4Z_{\odot}$ in accordance with the observations. The predicted Z values are very insensitive to the details of the collapse and on whether primordial material is still falling into the Galaxy or whether it ceased to fall long ago.

Talbot and Arnett (1973) too have obtained better agreement with observations from a model of constant IMF, an inhomogeneous collapse and enhanced star formation in the regions of high metal content.

Ostriker and Thuan (1973) have made detailed computations assuming a substantial amount of matter falling into the disk from a massive galactic halo. From a constant IMF (Salpeter's) they are able to explain the lack of metal-poor stars in the disk as well as the existence of some old metal-rich stars.

Finally, it should be mentioned that to produce a unique solution, or to narrow down the number of possible solutions, to the evolution of our Galaxy it will be necessary not only to study the chemical abundances in detail but also the photometric and the dynamical properties of the models (see for example Tinsley, 1972; Larson, 1973; Biermann and Tinsley, 1974; Ostriker and Thuan, 1973).

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DISCUSSION

E. M. Burbidge: Is there any controversy still about the super-metal-rich stars?

Peimbert: Yes, but the main points that I want to make are (i) that these objects are fairly old and (ii) that many astronomers agree on the existence of at least some super-metal-rich stars.

Rodgers: Well determined super-metal-rich stars, e.g. 31 Aql, δ Pov, all have old disk orbits, implying that their birthplaces were nowhere near the galactic nucleus.

Danziger: I believe there is at least one planetary nebula in the solar neighbourhood with a helium abundance significantly greater than the average for planetary nebulae. Frogel, Persson and I have recently analyzed the spectrum of the peculiar southern planetary NGC 6302, and we obtain a value of $[N(He^+)+N(He^{++})]/N(H^+) \approx 0.19–0.20$.

Przybylski: Last year I obtained high dispersion spectra of three stars in the Magellanic Clouds. In two of them, HD 6884 (SMC) and HC 269781 (LMC), the helium abundances are normal.

Similar results were obtained previously for two other extragalactic stars, HD 32034 (LMC) and HD 7583 (SMC).

van Woerden: You gave abundances for Cas A. Do they refer to the fast condensations or to the stationary ones?

Peimbert: The abundances refer to the fast moving knots. We believe that the material in the fast condensations was ejected during the supernova explosion, while the stationary condensations were expelled before the explosion and correspond to the outer layers of the presupernova object. The chemical abundances of these two systems are very different; the stationary condensations seem to be nitrogen rich while the fast condensations are definitely nitrogen deficient.

Oort: Why did you prefer Cas A to the Crab Nebula in the discussion of abundances in supernova shells? As the expansion of the Crab nebula has not been appreciably decelerated it could not have been seriously contaminated by interstellar gas.

Peimbert: To obtain abundances from forbidden lines, a knowledge of the electron temperature is needed. For Cas A we have some information on the temperature from observations of the [O III] 4363/5007 line intensity ratio. There are no published determinations of the electron temperature for the Crab Nebula so it is not possible to estimate the abundance of the heavy elements. In the case of the He/H abundance ratio the temperature dependence of both recombination lines almost cancels out, consequently the helium overabundance reported by Woltjer (1958) for the Crab Nebula seems to be real.

Freeman: Concerning the second parameter for the morphology of the horizontal branch in globular clusters: Does anyone know of any horizontal branch models for which [N/H] or [CNO/H] were varied independently of [Fe/H]?

Hartwick: Vandenberg and I have computed some initial horizontal branch models and find that a CNO overabundance of approximately two could explain the NGC 7006 red horizontal branch.

Rodgers: Because of the dominant influence of CO on free O or C, one must be wary of using CNO as a lump sum parameter to explain observed CN features.

E. M. Burbidge: It makes good sense that there should be no correlation between N, C, and O abundances, either in individual objects or in regions in galaxies, because they are produced by different nuclear processes. N is the prime indicator of hydrogen-burning in the CNO cycle in stars $\gtrsim 2\,M_\odot$ (its production and final ratio to C is dependent on the temperature in the hydrogen-burning region). In regions in galaxies, as G. Burbidge pointed out many years ago, since helium production is swamped by the high overall abundance of helium it is again N that is the prime indicator of H-burning in aggregates of high luminosity stars.

A. V. Peterson: In connection with Margaret Burbidge's remark, the O-type subdwarfs HZ 44, +25° 4655, HD 127493, show very strong He and N lines while the carbon and oxygen lines are very weak. Model atmosphere and abundance calculations give the He fractions by *number* for these stars as 0.38, 0.91, 0.50 respectively. The CNO *mass* fractions (e.g. $\mu_c N_c / \Sigma \, \mu_i N_i$) show carbon down by a factor of about 30, oxygen down by a factor of about 10, and nitrogen up by about a factor of 10 relative to solar abundances (Peterson, A. V.: 1970, Ph.D. Thesis, Cal. Inst. Tech.). Thus these abundances imply that hydrogen-burning has proceeded via the CNO cycle in these stars.

Kerr: Mass loss from evolved stars is important for the chemical evolution of a galaxy. G. R. Knapp and I have recently carried out high-sensitivity 21-cm observations of a giant elliptical, NGC 4472, and of a number of globular clusters, and we have still been unable to find neutral hydrogen in any of these systems. For NGC 4472 we can set a limit of $8 \times 10^7 \, M_\odot$, and for the globulars M22 and M4 our limits are about one solar mass. These limits are well below the values that might be expected from conventional mass-loss rates. Other explanations need to be considered, but it seems quite possible that the mass-loss rate for evolved stars is lower than that normally accepted.

Arp: Could gas have been blown out of NGC 4472?

Kerr: Not obviously.

Rickard: Dave Phillips at Cerro Tololo, and I at ESO, have used image-tube spectrographs to look for Hα and other hydrogen recombination lines in several 'open' globular clusters. So far we haven't detected any emission above the sky background and there seems to be little interstellar gas in the ionized form.

Kerr: In discussing Churchwell and Mezger's report of a very low abundance of ionized helium in some H II regions near the galactic centre, Dr Peimbert suggested as one of several possible explanations that the helium might be shielded by dust from the ionizing radiation. P. D. Jackson of Maryland points out in a forthcoming paper that there is at least one H II region near the Sun which has a low helium abundance, and this happens to be a very dusty nebula. This analogy supports the view that the helium in the regions near the centre is mainly neutral, due to shielding by dust.

Robinson: Can one say what fraction of the interstellar gas has been through nuclear processing in stars?

Peimbert: An estimate is possible using a model of galactic chemical evolution and studying the changes in parameters like D/H, ^{3}He/H or ^{4}He/H. At present the results are strongly model dependent.