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Stellar Abundances and the Origin of the Elements

Abundance analysis of stellar spectra reveals nuclear evolution in stars and galaxies

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Spectroscopic determination of the abundances of the chemical elements in stellar atmospheres provides us with most important indications on stellar evolution. In the vast majority of "normal" stars the chemical composition of the outer layers is, it turns out, unaffected (except for the highly proton-sensitive elements lithium, beryllium, and boron) by the energy-producing nuclear processes in the stellar interior. The composition of the atmosphere of such stars therefore gives us information on the composition of the interstellar matter out of which they originated. Other astronomical evidence enables us in many cases to calculate the age of these stars, or at least an upper limit for it.

There are, however, rare kinds of stars with atmospheres of highly anomalous composition—the helium-, barium-, carbon-, and other "peculiar" stars, usually designated according to the element whose spectral lines appear strengthened. In such cases we can investigate which nuclear processes were active in transforming the matter that we now observe directly, and we are faced with the problem of explaining how the star managed to "turn inside out."

Returning from "pathology" to the normal evolution of stellar matter, we notice that, in some of the oldest stars, the ratio of the abundance of any of the heavier elements (from carbon to barium) to the abundance of hydrogen—astronomers speak of this ratio as the "metal abundance"—is smaller by factors of up to ~ 200 than the corresponding ratio for the sun or the younger stars. One of the most exciting problems before us is that of finding whether the "metal abundances" and the abundance of helium (the end product of hydrogen burning) for these oldest stars differ from the corresponding ratios for the sun by the same factor.

Nuclear physicists can give us fairly clear indications as to what kinds of nuclear processes were active, and under what conditions of temperature and density, in producing the mixture of heavy elements that we observe in the sun and in most of the stars in the disk- and spiral-arm populations of our galaxy. But how—that is, in what kind of celestial bodies—did these processes take place? Discussion on the origin of the chemical elements has recently assumed even more exciting aspects since the first observations on the chemical composition of individual objects in external galaxies, differing in their general structure—their Hubble type—from our Milky Way, have become available.

Abundance Analysis of Stellar Spectra

In analyzing the spectrum of a star (*1*), we must determine simultaneously the constitution of the star's atmosphere and the star's chemical composition.

The constitution or "model" of the atmosphere is indicated by the effective temperature T_e, which describes the total energy flux per square centimeter of the stellar surface; by the surface gravity g (in centimeters per second per second); and by the velocity of statistically distributed atmospheric motions, the so-called turbulent velocity ξ_t (in kilometers per second). These turbulent velocities are between about 0.1 and 0.7 times the velocity of sound in the stellar atmosphere.

Interpreting individual Fraunhofer lines in terms of abundance (by number of atoms) ε, we find that ε always occurs multiplied by the transition probability for the line or by the oscillator strength f. (Instead of f one frequently uses the product gf, where g means the statistical weight of the lower energy level.) The f values can be calculated by quantum mechanics for the spectra of hydrogen, helium, and other one- and two-electron elements. For the complex spectra of elements such as iron and titanium, one must have recourse to laboratory measurements. For the stronger Fraunhofer lines another important atomic quantity is the damping constant γ sec^{-1}, which describes the line-broadening due to the finite lifetime of the energy levels (radiation damping) or due to collisions of the radiating atom with free electrons and hydrogen atoms.

The relation between the equivalent width W_λ (see Fig. 1) of a Fraunhofer line measured in the spectrum of a star and the abundance ε—or, rather, εgf—is given by the curve of growth (Fig. 2, solid line). For weak Fraunhofer lines (left-hand part of the curve) the relation is linear. As soon as W_λ reaches about the Doppler width $\Delta \lambda_D$, due to thermal and turbulent motions of the atoms, the absorption line becomes saturated and the curve of growth be-

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comes flat. For still stronger lines (right-hand part of the curve), line broadening by damping γ prevails.

I cannot go into the details of the theory of Fraunhofer lines (*1*) here, but we should carefully consider possible sources of error of the abundances ε determined from stellar spectra.

A relative error $\Delta W_\lambda / W_\lambda$ in the measured equivalent widths will—according to the solid line of Fig. 2—produce an equal relative error $\Delta\varepsilon/\varepsilon$ in the abundance for small W_λ. On the flat part of the curve of growth, $\Delta W_\lambda / W_\lambda$ will be multiplied by a factor of 3 to 5; on the square-root part (the right-hand part) of the curve, it will be multiplied by a factor of 2.

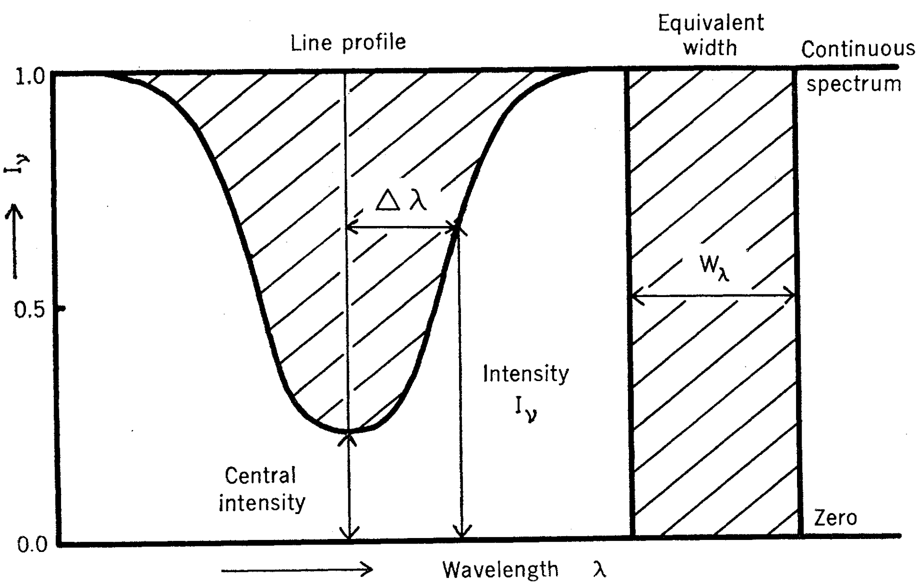

Fig. 1. Profile and equivalent width W_λ of a Fraunhofer line. The intensity of the continuum has been put equal to 1. The area under the line profile is equal to that of a completely "black" strip in the spectrum of width W_λ, usually measured in milliangstroms.

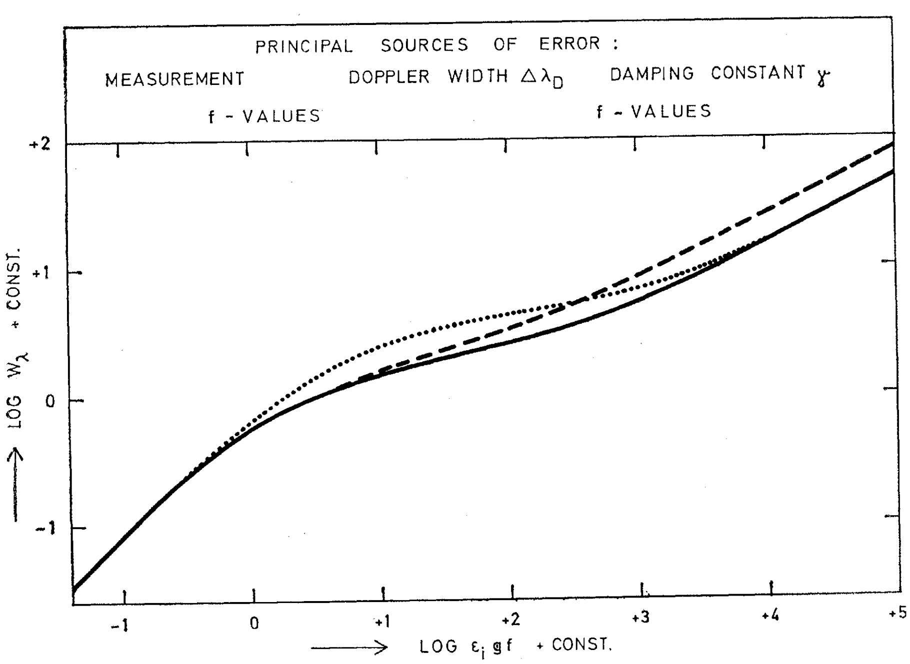

Fig. 2. Curve of growth. The equivalent width, log W_λ, is plotted over log ϵgf + constants where ϵ is the abundance, g is the statistical weight of the absorbing atomic state, and f is the oscillator strength of the line. Two changes are considered for comparison: (dotted curve) increase of the Doppler width $\Delta\lambda_D$ by a factor of 2; (dashed curve) increase of the damping constant γ by a factor of 3.2. The principal errors of the abundances obtained from equivalent widths W_λ are connected quite generally with the f-values and in particular, for weak lines, with errors of measurement in W_λ; for medium lines, with the Doppler width $\Delta\lambda_D$; and, for strong lines, with the damping constants γ.

The changes in the curve of growth that are due to an increase (mainly caused by turbulence) in the Doppler width $\Delta\lambda_D$ or an increase in the damping constant γ are indicated in Fig. 2. It may be seen that errors in $\Delta\lambda_D$ strongly affect the abundances ε derived from lines on the flat part of the curve, while errors in γ become important for lines on the right-hand part of the curve of growth.

Since we can determine directly only εgf, errors of the oscillator strengths affect weak and strong lines in the same way. At present, quantum mechanical calculations as well as laboratory measurements of the oscillator strength f and the damping constant γ are still beset with difficulties. The uncertainty of the numerical values can sometimes be eliminated by just *comparing* the abundance of an element in some star with that in a standard star, usually the sun. It should further be kept in mind that all abundance determinations for a star are strongly influenced by the choice of the effective temperature T_e and (to a minor degree) of the surface gravity g, which determines the atmospheric pressure. Particularly in the case of cool stars, the exponential functions in the Boltzmann and Saha formulas become very sensitive to temperature. On the other hand, T_e and g can only be obtained through applications of the Boltzmann and Saha equations to some suitably selected ionization equilibria. Even a systematic trend of the abundances from light to heavy elements in a star compared, for example, to the sun may easily be spurious when an inaccurate value for temperature is used, and may merely reflect the fact that the ionization potentials have some systematic trend along the periodic system. So the greatest possible care must be exercised in the determination of T_e.

In recent years there has been considerable dispute about the assumption of local thermodynamic equilibrium (LTE) inherent in the application of the equations of Boltzmann and Saha to stellar atmospheres. The objections raised by "NLTE-philosophers" against the assumption of local thermodynamic equilibrium—for example, in the solar atmosphere—have been clearly refuted by Holweger's (*2*) very thorough analysis of the solar Fraunhofer spectrum. Some minor residual disagreement between observations of the infrared solar continuous spectrum and LTE theory has been shown quite recently, by Labs and Neckel (*3*), to be due to faulty reduction of some measurements.

Abundances in the Atmospheres of Normal Stars

With all these critical remarks in mind, we attempt to obtain the most reliable abundance determinations for "normal" stars, which—as we shall see—all have the same composition within the present limits of accuracy of analysis.

The sun, our standard star, offers many advantages which are available in no other case. The spectrum can be measured with enormous dispersion, so that all details even of the narrow line profiles are fully resolved. The true continuous spectrum between the lines can be measured absolutely with great accuracy. In comparing center spectra and limb spectra, we look into the solar atmosphere from different angles. The effective temperature $T_e = 5780°K$ can be obtained directly from the solar constant, and the surface gravity g ($= 2.74 \times 10^4$ cm sec^{-1} sec^{-1}) is known from astrometric data.

Following earlier work by Russell (1929) and Unsöld (1948), a modern analysis was published in 1960 by Goldberg, Müller, and Aller (*4*) and an improved version was published in 1967 by Müller (*5*). These values, normalized as usual to $\log \varepsilon = 12$ for hydrogen, are reproduced in Table 1, column 3. In column 4 are given some other (mostly more recent) solar determinations which are considered to be of comparable accuracy.

With the sun are compared some very young stars in Table 1. Tau Scorpii (Bo V, $T_e = 32{,}800°K$, $\log g = 4.2$) has been reanalyzed by Scholz (*6*), using excellent spectra obtained at the Mt. Wilson Observatory by Traving. For ζ Persei (B1 Ib, $T_e = 27{,}000°K$, $\log g = 3.6$), we give Cayrel's (*7*) analysis, and for planetary nebulae we give the average values obtained by Aller (*8*). The red giants are represented in Table 1 by the abundance in ε Virginis (G8III, $T_e = 4940°K$, $\log g = 2.7$) determined relative to the sun by G. Cayrel and R. Cayrel (*9*). Obviously the differences between the values in the various columns of Table 1 are quite within the expected limits of accuracy. Even the subgiant δ Eridani, K0 IV, a very old disk star which fits into the color-magnitude diagram of NGC 188, has, according to Hazlehurst and Pagel (*10*), the same composition as the sun.

These results are quite remarkable, since they cover most of the lifetime of our galaxy. On the other hand, while the first two stars of Table 1 (the sun and τ Scorpii) are still on the main sequence, ζ Persei has reached the supergiant state and ε Virginis, somewhat more massive than the sun, is on the giant branch of the Hertzsprung-Russell diagram. The planetary nebulae are the envelopes of stars which are rapidly approaching the end of their career. Two conclusions may be drawn, (i) Throughout most of the lifetime of our galaxy, the interstellar matter (out of which the stars originated) has had practically the same composition. (ii) The chemical composition of the outer parts of the stars in our galaxy remained

Table 1. Abundances $\log \varepsilon$ for "normal" stars relative to $\log \varepsilon = 12$ for hydrogen.

Atomic number	Element	Abundance: Sun: Goldberg, Müller, Aller*	Abundance: Sun: Various †	Abundance: τ Scorpii ‡	Abundance: ζ Persei §	Abundance: Planetary nebulae ‖	Abundance: $\log \varepsilon/\varepsilon_\odot$ ε Virginis ¶
1	H	12.00	12.00	12.00	12.00	12.00	0.00
2	He		11.2	11.12	11.31	11.25	
3	Li	0.90	0.97				
			≤ 0.38				
4	Be	2.34					
5	B	3.6					
6	C	8.51	8.51	8.21	8.26	8.7	−0.12
			8.55				
7	N	8.06	7.93	8.47	8.31	8.5	
8	O	8.83	8.77	8.81	9.03	9.0	
9	F					5.5:**	
10	Ne			8.98	8.61	8.6	
11	Na	6.30	6.18				+0.30
12	Mg	7.36	7.48	7.7	7.77		+0.04
13	Al	6.20	6.40	6.4	6.78		+0.14
14	Si	7.24	7.55	7.66	7.97		+0.13
15	P	5.34	5.43				
16	S	7.30	7.21	7.3	7.48	8.0:	+0.09
17	Cl					6.5:	
18	A			8.8:		6.9:	
19	K	4.70	5.05				
20	Ca	6.04	6.33				+0.10
21	Sc	2.85					−0.07
22	Ti	4.81					−0.07
23	V	4.17					−0.04
24	Cr	5.01					0.00
25	Mn	4.85					+0.07
26	Fe	6.80		7.4			+0.01
27	Co	4.70					−0.03
28	Ni	5.77					+0.03
29	Cu	4.45					+0.06
30	Zn	3.52					+0.05
31	Ga	2.72					
32	Ge	2.49					
37	Rb	2.48	2.63				
38	Sr	3.02	2.82				+0.02
39	Y	3.20					−0.17
40	Zr	2.65					−0.15
41	Nb	2.30					
42	Mo	2.30					
44	Ru	1.82					
45	Rh	1.37					
46	Rd	1.57					
47	Ag	0.75					
48	Cd	1.54					
49	In	1.45					
50	Sn	1.54					
51	Sb	1.94					
56	Ba	2.10	1.90				−0.09
57	La	2.03					−0.08
58	Ce	1.78					−0.08
59	Pr	1.45					+0.37
60	Nd	1.93					+0.06
62	Sm	1.62					+0.01
63	Eu	0.96					
64	Gd	1.13					
66	Dy	1.00					
70	Yb	1.53					
72	Hf						+0.18
82	Pb	1.63	1.93				

* See *4*, *5*. † Various recent determinations. Value for He, from *69*; values for Li, from *70* (abundance in sunspots) and *71*, respectively; for C, from *72* (CI and CH lines) and *73*, respectively; for N, O, Na, Mg, Al, Si, P, S, K, Ca, Rb, Sr, and Ba, from *73*; for Pb, from *71*. ‡ From Scholz (*6*). § From Cayrel (*7*). ‖ From Aller (*8*). ¶ From Cayrel and Cayrel (*9*) ($\odot$ = the sun). ** The colon signifies lower accuracy.

Table 2. Abundances of elements in helium stars relative to log ε (He) = 11.61.

Atomic number	Element	Abundances				
		HD 160641*	HD 168476†	HD 124448†	BD + 10° 2179†	HD 30353‡
1	H		< 7.1	< 7.8	8.49	7.6
2	He	11.61	11.61	11.61	11.61	11.6
6	C	8.66	9.16	9.01	9.51	6.2
7	N	8.77	8.35	8.38	8.67	9.2
8	O	8.91	< 8.3	< 8.4	< 8.2	7.5
10	Ne	9.42	9.05			8.5
12	Mg	7.61	7.53	7.75	7.2	
13	Al		6.19	6.61	5.8	
14	Si	7.61	7.12	7.21	7.42	7.6
15	P		6.06			
16	S		6.75	7.19		7.8
18	A			6.9		
20	Ca		6.00	6.40	5.91	
21	Sc		4.3:§			
22	Ti		5.98	6.3:		
23	V		4.65			
24	Cr		5.20	4.8:		
25	Mn		4.57	4.84		
26	Fe		7.42	7.58		
28	Ni		5.4:	5.2:		

* See *12*. † See *13*. ‡ See *15*. § The colon signifies lower accuracy.

mostly unaffected by nuclear processes which, in connection with the production of energy, must have considerably altered the chemical composition of their interiors.

The well-known fact that the vast majority of stars (> 95 percent) can be classified by two parameters, spectral type and luminosity class, corresponding to the "theoretical" T_e and g, clearly shows that all these stars have the same composition, too, and that the foregoing conclusions apply to them.

Evidence of Nuclear Reactions from Abundances

There can, however, be no doubt that the generation of energy in the interior of the stars is due to nuclear reactions. With increasing central temperatures we expect the following sequence of processes: (i) burning of hydrogen into helium, first by fusion, then by the CNO cycle; (ii) burning of helium into carbon-12; and (iii) burning of carbon into still heavier elements. At extremely high temperatures the elements of the iron group may be produced in a kind of frozen-in thermodynamic equilibrium (known as the *e* process), and the heavier nuclei may be affected by neutrons—the so-called *s* (for slow) and *r* (for rapid) processes. All these nuclear problems have been studied, and presented in considerable detail, by E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle (see *11*, the much-quoted "B²FH paper"); I therefore need not go into details.

Let us attempt now to find spectroscopic evidence for these nuclear transformations.

1) Helium stars are hot objects with weak hydrogen and strong helium lines. In HD 160641, analyzed by Aller (*12*), and in HD 168476, HD 124448, and BD + 10° 2179, analyzed recently by Hill (*13*), the relative abundances of the heavier elements are quite normal (Table 2). Hydrogen is missing or much rarer than helium. The observed helium abundance can be quantitatively explained by the assumption that all the hydrogen has been burnt into helium. Starting (see Table 1) with log ε(H) = 12.00 and log ε(He) = 11.20, and making one helium atom out of four hydrogen atoms, we would obtain log ε(He) = 11.61, exactly as observed. In HD 160641, the CNO group remained almost unaffected; in this star the hydrogen, therefore, has probably been burnt by the fusion process only.

Things are quite different with the helium star HD 30353. According to the first analysis made by Nariai (*14*), helium and the elements from magnesium to strontium behave as they do in the already mentioned helium stars. But, more recently, Wallerstein, Greene, and Tomley (*15*) showed that in HD 30353 the abundances of carbon and oxygen are much reduced, while the abundance of nitrogen is strengthened, relative to the abundances in normal stars. These findings point to the idea that, while the CNO process becomes stationary—that is, becomes a real cycle—most of the mass originally present as carbon, nitrogen, and oxygen is transformed into nitrogen. Beginning with average abundances taken from Table 1, one easily calculates log ε(N) to be 9.14, a value in surprisingly good agreement with the data of Table 2.

In the intermediate objects HD 168476, HD 124448, and BD + 10° 2179, the CNO cycle may have done some of the hydrogen burning and the carbon may have been, at higher temperature, "filled up" by helium burning.

The helium stars seem to be a mixed lot, not only as judged by their composition. Many of them appear, from their high radial velocities, to be members of halo population II (discussed below); these must represent a late stage of stellar evolution, having masses no smaller than about 1.5 solar masses. On the other hand, σ Orionis E, a massive type-B star on the main sequence of the very young Orion association, has a helium-hydrogen ratio 4.7 times larger than normal, according to Chadeau (*16*).

2) Carbon stars are cool (red) giants, in which the band spectra of CH, C_2, and CN, as well as atomic lines of carbon, indicate enhanced abundance of carbon. Here "nuclear escalation" must have reached the stage of helium burning. Again we recognize several subgroups.

The CH stars are distinguished by a rather strong CH band. Wallerstein and Greenstein (*17*) analyzed HD 26 and HD 201626 by comparison with ε Virginis (Table 1). In both stars the heavy elements are reduced relative to hydrogen, by factors of 5 and 30, respectively. This, together with their high radial velocities, makes them members of halo population II. In a further study of the abundances of the heavy elements, now relative to iron, in HD 26 and HD 201626 by comparison with ε Virginis, it turns out that the abundances for the heavy elements up to zirconium-40, except for carbon, are normal; carbon is five or six times more abundant in the CH stars. However, the quite heavy elements, from barium-56 on, are all overabundant by a factor of about 15. While the carbon abundance must be connected somehow with the energy-generating processes, the overabundance of barium and the heavier elements can have originated only through neutron irradiation, the probability of occurrence of proton processes being much too small in these heavy nuclei.

Very interesting information on all the carbon stars is provided by the isotope ratio C^{12}/C^{13}, as obtained from isotope bands by McKellar (*18*), Climenhaga (*19*), and others. This ratio varies between high values ($\sim$ 90) similar to those obtained for terrestrial carbon and for the sun—for which Richter and Tonner (*20*) recently determined 100 $\pm$ 30 from the CH band —and low values of $\sim$ 5. A high C^{12}/C^{13} ratio ($\sim$ 100) seems to indicate "normal" stellar matter, described by the data of Table 1, while calculations by Caughlan and Fowler (*21*) show that the CNO cycle produces, throughout the temperature range 10^7 °K to 10^8 °K, an almost constant ratio $C^{12}/C^{13} \approx 4$.

In the CH stars, high as well as low C^{12}/C^{13} ratios occur, showing again that the details of the events were not uniform.

In the ordinary carbon stars the ratio C^{12}/C^{13} seems always to be low. In other respects, analysis of the spectra of such cool giants is extremely difficult, and it may be too early to make general statements (*22*).

The hydrogen-deficient carbon stars are represented by the well-known variable R Coronae Borealis. Following Berman's (*23*) pioneer work, Searle (*24*) carefully reanalyzed this variable, Danziger (*25*) analyzed RY Sagittarii, and Warner (*26*) analyzed several similar stars. In Table 3 are compared the abundances *by weight*, of hydrogen, helium, carbon, and the sum of all of the heavier elements for R Coronae Borealis, RY Sagittarii, and the sun. The abundances of the heavier elements up to europium-63 agree to within about $\Delta \log \varepsilon = \pm 0.3$ with those on the sun. Extending his analysis into the infrared, Danziger could even show that, for RY Sagittarii, the abundances of nitrogen and oxygen agree to within $\Delta \log \varepsilon = \pm 0.5$ with those on the sun. On the other hand, in various hydrogen-deficient carbon stars, hydrogen is highly underabundant, helium is moderately overabundant, and carbon is overabundant by factors ranging from about 3 to 20. In the carbon bands, only the isotope C^{12} can be recognized, C^{12}/C^{13} being > 50. These results, summarized in Table 3, mean that most of the hydrogen has been transformed into helium and a moderate fraction of the helium has been transformed into C^{12}. No definite trace of the CNO cycle or of neutron irradiation can be recognized. On the other hand, in most ordinary carbon stars the isotope ratio is $\sim$ 5, a value which may indicate that carbon formed out of helium was later subject to the CNO cycle.

Table 3. Abundances of elements by weight (in percentages) in the hydrogen-deficient carbon stars R Coronae Borealis (*24*) and RY Sagittarii (*25*) compared with abundances in the sun.

Star	H	He	C*	Heavy elements†
Sun	0.63	0.34	0.003	0.027
R Coronae Borealis	.0005	.91	.067	.022
RY Sagittarii	.0001	.87	.10	.026

* $C^{12}/C^{13} > 50$. † The relative abundances of N, O, and the heavier elements up to $Z = 63$ for these two carbon stars are the same as for the sun, to within factors of 2 to 3.

The barium stars are recognized by the unusual strength of the barium resonance doublet—$\lambda\lambda$ = 4554 and 4934 angstroms. Warner (*27*) and Danziger (*28*) have carefully investigated this group of stars. In Fig. 3 are plotted the abundances relative to the sun for the two barium II stars HD 83548 and HD 116713, which were analyzed quite independently by Warner and Danziger [from Danziger's log ε relative to α Boötis, 0.4 was subtracted, following R. Griffin and R. Griffin's (*29*) recent analysis of α Boötis].

Figure 3 demonstrates how easily systematic "abundance differences" between, for example, the iron group and the quite heavy elements can occur as a result of slight differences in determinations of the general atmospheric parameters. We can, however, infer from observation that the abundances of the elements of atomic number $Z > 35$ are probably increased by factors of about 10 (range, 5 to 25). This may be taken as a fairly clear indication of neutron irradiation. From the viewpoint of spectroscopy, there is probably not yet justification for going into finer details (see, for example, *27, 28, 30*).

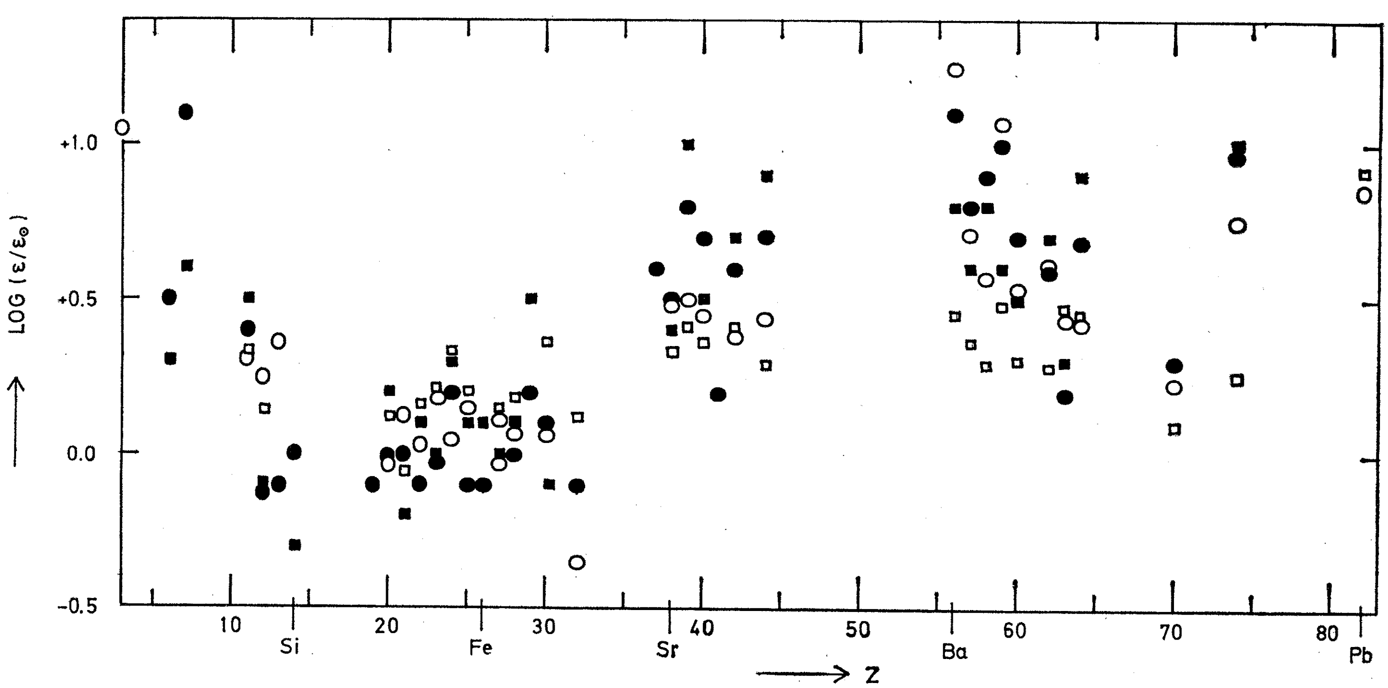

Fig. 3. Abundances in barium II stars relative to the sun: $\varepsilon/\varepsilon_\odot$. (Rectangles) HD 83548; (circles) HD 116713. (Open symbols) Values from Warner (*27*); (solid symbols), values from Danziger (*25*).

In the still cooler S stars, quantitative work of some accuracy has so far not been possible, due to complications connected with low stellar temperatures. However, the general features of the barium II stars persist. The great strength of the atomic lines of zirconium, lanthanum, yttrium, strontium, barium, and other heavy elements and of the bands of ZrO, LaO, YO, . . . clearly demonstrates overabundances for $Z \geqslant 38$. The view that these elements originated from neutron processes receives further support from Merrill's (*31*) well-known discovery of technetium lines in many S stars. Recent calculations on stellar evolution along the red giant branch lead to times which are indeed of the same order of magnitude as the half-life of Tc_{43}^{99}—namely, 2×10^5 years.

We should consider here, in a slightly more general way, the question of why and how the matter in the atmospheres of only a small percentage of all the stars underwent considerable nuclear transformation.

The theory of the quiet evolution of single stars has so far not indicated any possible mechanism for bringing partly burnt material to the surface, in agreement with observation.

In close binary systems, however, it may happen that the more massive component, in approaching the red giant stage, swells over the innermost equipotential surface, which envelops both components, and that its outer parts flow over to the less massive component, and burnt-up material comes to the surface. This process has been followed theoretically in a number of cases by Kippenhahn and his collaborators (*32*).

Quite recently Van den Heuvel (*33*) has shown that the origin of the peculiar A stars (Ap stars) and the metallic line stars (Am stars) can be explained on this basis. In the course of the evolution of close binary systems, partly burnt matter from the interior of the more rapidly developing component is transferred to the upper layers of the other component. In the Ap stars, matter differing in composition from the surrounding matter seems to be located in "spots" on the surface, which differ also in magnetic field. Such a blob of plasma, differing in composition from its surroundings and kept together by a frozen-in magnetic field, may have some similarity to the so-called plasmoids known from laboratory work.

Furthermore, according to Thomas (*34*), the "flash" phenomena (nuclear processes starting suddenly in a degenerate zone) seem to be able to bring partly burnt material to the surface of a star under certain circumstances.

We should also keep in mind the fact that some of our present quantitative ideas on the evolution of single stars may not be perfect. In studying convective zones one generally uses the very crude theory of mixing length. A more accurate treatment, involving considerations of stellar rotation and magnetic fields, might well, in some cases, lead to a mechanism whereby convective zones would reach the surface.

The atmospheres of all the "anomalous" stars so far investigated contain matter which has been affected by nuclear reactions in the stellar interior. In the main, composition of these stars deviates from "normal" so strongly that their spectral anomalies were noticed—though not interpreted—quite early.

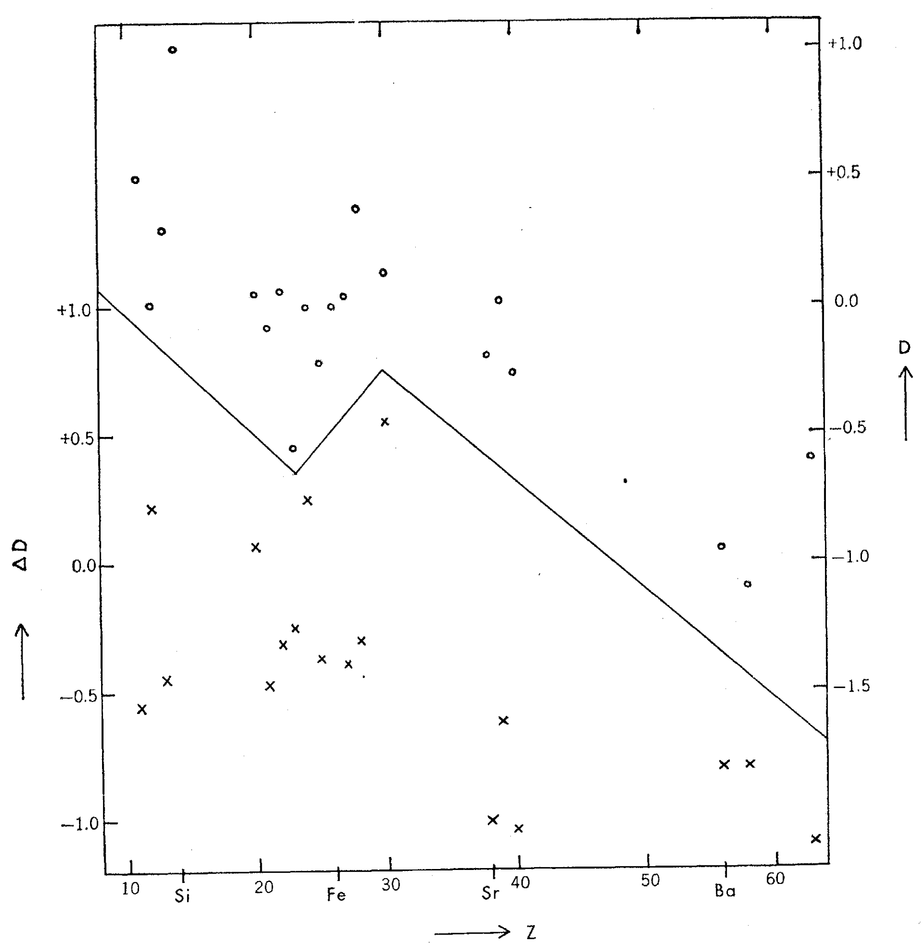

Fig. 4. Abundances of elements in the metal-deficient red giant HD 122563. (Circles and scale at right) Abundances relative to those in the sun and to the abundance of iron: $D = \log (\epsilon/\epsilon_{\odot}) - \log (\epsilon_{Fe}/\epsilon_{Fe,\odot})$. [After Pagel (*41*).] (Crosses and scale at left) Abundance differences ΔD between the analytical results of Wallerstein *et al.* (*40*) and those of Pagel (*41*) based on the same observations. Not only chance differences but also large systematic effects depend on the values adopted for T_e, g, turbulence, and so on.

Metal-Deficient Stars in the Galaxy

We now turn to the "metal-deficient" stars. Members of one important group (corresponding to the normal main sequence stars) are usually called subdwarfs, for the merely historical reason that, due to their fainter metallic lines, they were originally classified "too early" and so seemed to be located below the main sequence. Modern classification, based on T_e, M_v, and other parameters, places them near the main sequence.

The best-investigated case is that of HD 140283, originally classified as subdwarf A2, then as subdwarf F5. Baschek's (*35*) analysis gave $T_e = 5940°K$ and $\log a = 4.6$, values closely resembling those for the sun, G2V. The chief difficulty concerning the abundance determinations pertains to T_e. For example, if the value taken for T_e is too high, the faintness of the metallic lines is partly explained as ionization and the value for metal deficiency comes out too small, and vice versa. When Baschek's value for T_e is used, the abundances, relative to hydrogen, of all the elements from carbon to barium turn out to be too low by a factor of 200, or by $-\Delta \log \varepsilon = 2.3$, relative to the sun. Results of a more recent analysis, by Cohen and Strom (*36*), agree with Baschek's results probably to within the usual errors for the whole procedure. Other subdwarfs have different $\Delta \log \varepsilon$, but one that is consistent for all the elements.

Kodaira (*37*) analyzed the spectrum of the horizontal-branch star HD 161817 ($T_e = 7630$°K; $\log g = 3.0$), which has $-\Delta \log \varepsilon = 1.1$. This most interesting star, according to Eggen and Sandage (*38*), seems to be accompanied in space by the G5 subdwarf Wilson 10367 (= LPM 661), which has almost the same (highly unusual) space velocity vector. Analysis of the spectrum of Wilson 10367 by Baschek (*39*) showed that its composition (insofar as this can be ascertained for such a faint star) cannot be distinguished from that of HD 161817. This may be taken as further evidence that the matter which we see now in the atmosphere of the horizontal-branch star has not changed its composition since it left the main sequence.

In Table 4 are presented elemental abundances for HD 140283 and HD 161817 relative to the sun. In all cases we have subtracted from $\log \varepsilon$ the average metal underabundance found from the analysis itself. Obviously no differences for individual elements from carbon to barium can be detected outside the usual errors of analysis.

Wallerstein, Greenstein, Parker, and Helfer (*40*) detected several red giant stars having unusually low metal abundances, which, with respect to their evolutionary status, would come between the main sequence star HD 140283 and the horizontal-branch star HD 161817. Best suited for quantitative work is HD 122563 (magnitude, 6.2) whose color index B–V (= 0.90) corresponds about to K0 V. The observational material of Wallerstein *et al.* was analyzed again by Pagel (*41*). The average metal underabundance, $-\Delta \log \varepsilon$, as determined by Wallerstein *et al.* and by Pagel, turned out to be 2.9 ± 0.2 and 2.55 ± 0.25, respectively—slightly more pronounced than the average for HD 140283. Possible abundance differences for individual elements have aroused considerable discussion. In Fig. 4 are shown (circles) the abundances, relative to iron, from Pagel's analysis (*41*) and (crosses) the extent to which the abundances as determined by Wallerstein *et al.* (*40*) exceed the abundances as determined by Pagel *et al.* (*41*). Obviously, small differences in the basic atmospheric parameters adopted result in very considerable accidental and systematic differences in the abundance values. Therefore we probably should not accept such apparent individual effects without question.

Table 4. Abundances in the metal-deficient subdwarf HD 140283 [from Baschek (*35*)] and the horizontal-branch star HD 161817 [from Kodaira (*37*)] relative to the sun, ⊙. In order to make it easier to recognize possible effects in individual elements, the average deficiencies have been subtracted.

Atomic number Z	Element	HD 140283 ($\log \varepsilon/\varepsilon_\odot$ +2.32)	HD 161817 ($\log \varepsilon/\varepsilon_\odot$ +1.11)
1	H	+ 2.32	+ 1.11
6	C	− 0.5	− 0.26
11	Na	− 0.30	− 0.05
12	Mg	+ 0.01	+ 0.18
13	Al	− 0.26	− 0.26
14	Si	+ 0.07	− 0.19
20	Ca	− 0.03	+ 0.09
21	Sc	+ 0.61	+ 0.21
22	Ti	+ 0.05	+ 0.25
23	V		− 0.42
24	Cr	− 0.09	− 0.27
25	Mn	+ 0.35	− 0.43
26	Fe	− 0.16	− 0.10
27	Co	+ 0.02	+ 0.12
28	Ni	− 0.31	+ 0.11
38	Sr	0.00	+ 0.24
39	Y		− 0.19
40	Zr		− 0.13
56	Ba		− 0.05

Abundance differences for individual elements have been proposed again and again in the literature, frequently in connection with speculations on their origin from nuclear processes. Most of these proposed individual effects cannot be accepted as established, for the following reasons. (i) The proposed abundance differences are mostly of the same order of magnitude as the average error of the analysis. (ii) Since a star highly deficient in metals, like HD 140283, shows no such effects, why should these effects be large in stars less deficient in metals? (iii) It is remarkable that the observed deficiency is the same for carbon, members of the iron group, and heavy elements like strontium and barium and shows no relation to the various types of nuclear effects described in the preceding section.

In order to obtain more accurate values for the abundances of individual elements, in general more attention should be paid to the fact that the turbulence ξ_t in stellar atmospheres shows considerable variation among stars having the same spectral type and luminosity. For some elements—for example, manganese—the hyperfine structure of the lines should be taken into account. Again, the importance of very careful temperature determination cannot be overemphasized.

There are also stars in which the abundances, relative to hydrogen, of the heavier elements appear too high relative to the ratios for the sun. In order to make sure that these rather small effects are genuine, the general constants of the atmosphere must be determined very accurately. Beta Virginis F8V, classified by Roman as a strong-line star and supposed, by Wallerstein, to have high abundances of the heavy elements, was analyzed by Baschek, Holweger, Namba, and Traving (*42*); they found the ratios of the abundances, relative to hydrogen, of all the elements from carbon ($Z = 6$) to lanthanum ($Z = 57$) to be twice as high ($\Delta \log \varepsilon = 0.3 \pm 0.2$) as the corresponding ratios for the sun. The observations, however, can be interpreted also in another way: since helium cannot possibly be observed in such a cool star, we might just as well assume that the abundances of the heavy elements are normal but that half the original hydrogen has been transformed into helium by fusion, and that $\log g$ should be slightly changed.

Helium Abundance in Galactic Objects

Since helium plays such a distinguished role in the production of nuclear energy by the stars and possibly also in general nucleogenesis, we inquire into its abundance, first in normal, then in metal-deficient, stars.

In general, He I and He II lines are observed only in stars hotter than ~ 10,000°K. The only exceptions are the solar prominences, for which, however, the degree of ionization is rather uncertain. Accurate determinations (*43*) are possible, also, for planetary and galactic nebulae.

In Table 5 are presented selected data. To the data given, from the two best analyses of hot stars, we could add data for τ Scorpii and 10 Lacertae, obtained by Traving, and for γ Pegasi, obtained by Aller and Jugaku, without altering the average value. The value for the Orion nebula NGC 1976 is a weighted average of four determinations. The data for planetary nebulae are also averages over many objects, reduced in accordance with recent theoretical work. The value for the sun is derived from emission lines in prominences, although theory concerning these lines is not yet completely clear. In any case, this value is probably better than values obtained from solar cosmic rays and the solar wind. These phenomena originate in regions with very big mean free paths; where large selective effects may be at work.

In Table 6 are given the few data that are available on metal-deficient objects. For the halo B star BD + 33° 2642, Traving (*44*) obtained for the elements carbon, nitrogen, oxygen, magnesium, and silicon an underabundance factor of 5 to 10, while he found the helium-hydrogen ratio to equal that for τ Scorpii or to be smaller by 30 percent at most. In the 12.9-magnitude star Barnard 29 (a member of the metal-poor globular cluster M13), for which the basic parameters are very uncertain, he found a helium-hydrogen ratio probably half that for τ Scorpii. A quite reliable ratio was obtained by O'Dell, Peimbert, and Kinman (*45*) for the planetary nebula K648, which is a member of the metal-deficient globular cluster M15 (= NGC 7078). In this unique object, oxygen and neon are underabundant, relative to hydrogen, by a large factor, but the helium-hydrogen ratio is perfectly normal. Also, for the high-velocity ($V_r = 193.9$ kilometers per second) planetary nebula NGC 6644 (which probably originated from a subdwarf), O'Dell and his associates obtained a normal helium-hydrogen ratio. For the objects of Table 6, the abundance of helium is norml despite considerable underabundance of the heavier elements.

More recently, however, Sargent, Searle, and others (*46*) have found high-latitude B stars with quite weak helium lines. Helium-line weakness, however, does not seem to be clearly correlated with metal-line weakness. Moreover, in the Orion complex, normal and helium-deficient B stars seem to occur close together (*47*).

Table 5. Helium-to-hydrogen abundance ratio (by number of atoms), log H/He, for objects having normal abundances of the heavy elements in a galactic spiral-arm and disk population.

Object	Log H/He	Reference
Orion nebula NGC 1976	0.84	(*45*)
B stars		
τ Scorpii	.88	(*6*)
ζ Persii	.69	(*7*)
Planetary nebulae	.76	(*45*)
Plenetary nebulae	.75	(*8*)
Planetary nebulae	.80	(*74*)
Sun (prominences)	.80	(*69*)
Most probable value	.79 + 0.05*	

* By number of atoms, H/He = 6.2/1; by mass, X/Y = 61/39.

Table 6. Helium-to-hydrogen abundance ratio (by number of atoms), log H/He, for metal-deficient objects.

Object	Log H/He	Reference
B star BD + 33° 2642	0.95	(*44*)
Planetary nebula K648 in M15	.74	(*45*)
High-velocity planetary nebula NGC 6644	.85	(*45*)

Abundances in Other Galaxies

In connection with the origin of the elements, it is extremely interesting to compare abundances in other galaxies with those in our Milky Way.

In the Large and the Small Magellanic Cloud (LMC and SMC), Feast, Thackeray, and Wesselink (*48*) have taken spectra of B0 Ia to K5 Ia supergiants, a dispersion of 30 to 85 angstroms per millimeter, and have compared them with corresponding spectra of stars in our galaxy. Code and Houck (*49*) compared spectra obtained with a dispersion of 87 angstroms per millimeter for the LMC supergiant HDE 269700, B2 Ia+, and the galactic standard ζ^1 Scorpii = HD 152236, both of which have an absolute magnitude of − 9.0.

In all these studies, on about 26 elements, from hydrogen to barium, no difference whatsoever between stars in our galaxy and stars in the Magellanic Clouds could be detected. Every astronomer who has had some experience in comparing stellar spectra will conclude therefrom that the abundances in population-I stars of our galaxy and our neighbor galaxies agree to within a factor of ~ 1.5. Przybylski (*50*) has compared spectrophotometrically HD 33579, ~A2 Ia, the brightest star of the Large Magellanic Cloud, with the similar, but slightly less bright, α Cygni. The abundances, relative to hydrogen, of iron, chromium, and titanium agree, within the acceptable limits of accuracy; these limits, however, are probably wider than those in the simple comparison of spectra.

Besides stars, gaseous nebulae in the Magellanic Clouds have been analyzed for the abundances of hydrogen, helium, oxygen, and (roughly) sulfur. Johnson (*51*), Faulkner and Aller (*52*), and Mathis (*53*) have investigated the 30 Doradus nebula in the Large Magellanic Cloud; previously Aller and Faulkner (*54*) had analyzed the nebula NGC 346 in the Small Magellanic Cloud. Bearing in mind the fact that the theoretical factors involved in reducing line intensities to abundance ratios have undergone slight changes in the course of time, we can say, in summary, that the abundance ratios of hydrogen, helium, oxygen, and probably also sulfur in both Magellanic Clouds and in our galaxy agree to within about 50 percent; no systematic differences can be made out.

For remote galaxies, few spectrophotometric data are available so far. In the *Sc* galaxy M33, Mathis (*55*) determined, for the gaseous nebula NGC 604, the helium-hydrogen ratio and found it to agree, to within 10 percent, with that for similar galactic objects. In the Andromeda galaxy, M31, Schmidt (*56*) compared the λ 5876 line of helium with the Hβ line of hydrogen at distances of 25′, 70′, and 89′ from the center of the galaxy and found that the helium-hydrogen ratios agreed with each other and with values for our galaxy to within a factor of about 2.

For other galaxies, only integrated spectra can be obtained, but it is a fact of enormous importance that these can be reproduced very well through suitable superposition of the spectra of common galactic stars, or, in some cases, even fit quite well with the spectra of galactic star clouds. This means that the hydrogen-metal ratio and also the relative abundances of the prominent elements (the strong H + K lines can be recognized even in faint galaxies) are the same in most galaxies, within rather narrow limits. That is so all through the Hubble sequence, from giant ellipticals like NGC 205, through our galaxy and M31, to the Magellanic Clouds of type Irr I.

We cannot tell at present whether in dwarf galaxies it is only the bright stars or all the stars that are deficient in metals.

We do not know of any object (except for "anomalous" stars) in which the hydrogen-helium ratio deviates significantly from 6.2/1. In all galaxies the relative abundances of all the heavier elements from carbon to barium and the hydrogen-to-metal ratios have the same values for the vast majority of stars. Color-magnitude diagrams, however, show that there occur (old?) objects with lower abundance of metals. On the other hand I should emphasize the fact that everywhere in the universe the metal abundance reaches the same well-defined upper limit.

Origin of the Elements

After the decline of the Lemaître-Gamow "big bang" theory, the origin of the elements and of their abundance distributions was discussed principally with regard to our galaxy (*57*). The galaxy consists mainly of three different stellar populations (*58*), described in Fig. 5 and Table 7.

Observations show that low metal abundance is most clearly correlated with great eccentricity and high inclination of the galactic orbits; it is a property of the extreme halo population II.

Even the oldest stars of the disk population have, in the main, a metal abundance which cannot be distinguished from that of the sun or the younger, spiral-arm population—that is, all abundances in the disk and spiral-arm populations are the same, to within an error of, at most, 50 percent. That the average composition of matter in the galaxy has not changed within the past $\sim 10^{10}$ years is not astonishing, since, with its present luminosity, the galaxy would have burnt in this time only about 2 percent of its total hydrogen.

Assuming that the galaxy originated as a mass of almost pure hydrogen and that most of the heavy elements were produced in its youth, we attempt to estimate the time available for "heavy-element cooking." Comparison of the color-magnitude diagrams of globular clusters like M92 with those of the oldest open clusters like M67 and NGC 188 (see, for example, *59*) gives an upper limit which at present cannot be placed lower than about a billion years.

If one further assumes that the galactic disk was formed by collapse out of the halo, then simple mechanical considerations give a much narrower limit: the time of free fall must be of the same order as the times of revolution—about 1 to 3×10^8 years. The same conclusion was reached by Eggen, Lynden-Bell, and Sandage (*60*) from the nonconservation of the adiabatic invariants of the stellar orbits during the supposed collapse.

These adiabatic invariants are, by the way, well known to atomic physicists as the orbital characteristics which were "quantized" in the Bohr theory of penetrating and outer electron orbits. From the theory of galactic collapse we must therefore conclude that practically all the heavy elements were produced, by successive processes of stellar evolution, within 1 to 3×10^8 years.

If one assumes further—as some authors do—that the original matter was not only metal-deficient but also helium-deficient, then production of the present abundance of helium in such a short time would require that our galaxy during the first few 10^8 years of its life was about 10^3 times brighter than it is nowadays (see, for example, *61*).

On the other hand, if one assumes that the helium-hydrogen ratio is about the same everywhere and if, like Peebles (*62*) and Wagoner, Fowler, and Hoyle (*63*), one ascribes the formation of helium only to a "big fireball" at the time of origin of the universe, then little can be inferred about the initial brightness of the galaxy.

The hypothesis (which seems to be fairly generally accepted at present) that at least 99 percent of the heavy elements were produced within a period of 1 to 3×10^8 years, during the early collapse of the galaxy, meets with several very serious difficulties.

1) It does not explain why the abundance distribution of all the heavier elements is the same in the metal-deficient halo population II and in the disk and spiral-arm populations. One should bear in mind the fact that carbon is affected by the energy-producing processes; the production of the iron group requires different conditions (the *e* process), and the heaviest group is mostly affected by neutrons. In the "pathological" stars we have seen how different types of nuclear processes affect the abundances in different and quite pronounced ways. Should we expect their joint effect to reproduce exactly the relative abundance distribution of the heavy elements which existed at the time of subdwarf formation?

2) The idea, which is indicated—though perhaps at present not proved

Table 7. Main stellar populations in our galaxy (Fig. 5).

Stellar population	Galactic orbits		Age (years)*	Brightest stars	Metal abundances
	Form	Inclination (i)			
Halo population II	Elongated	$0° < i < 90°$	$(10 \pm 4)\ 10^9$	Red giants, $-3^{M}.5$; CN weak	1/200 to 1/5
Disk population	Circular	Small	$\leqslant (10 \pm 4)\ 10^9$	Red giants, $0^{M}.0$; CN strong	Mostly normal
Spiral-arm population I	Circular	Small	10^5 to 10^{10}	Blue O and B; -7 to -8^{M}	Normal (solar)

* Determined from color-magnitude diagrams of (i) globular clusters, in the case of the halo population, and (ii) open clusters or stellar associations in the case of the disk and spiral-arm populations.

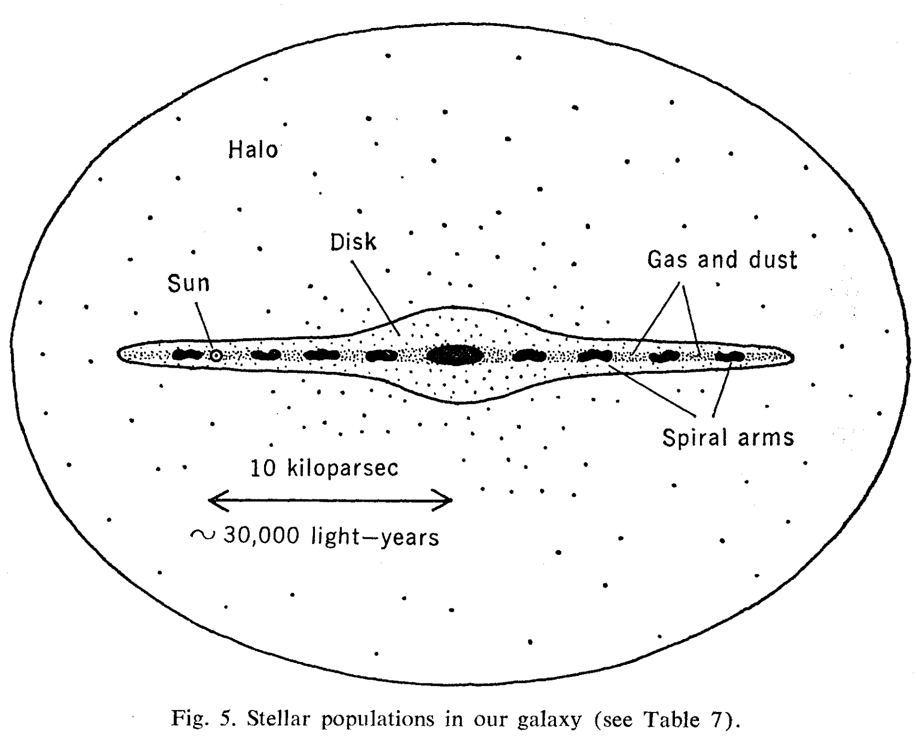

Fig. 5. Stellar populations in our galaxy (see Table 7).

—by observation, that the helium-hydrogen ratio is constant and independent of metal abundance would be very hard to reconcile with the proposed hypothesis.

3) Why should the metal production have been stopped at the same hydrogen-metal ratio in galaxies distributed all along the Hubble sequence, from the Magellanic Clouds (Irr I) to our galaxy and the Andromeda galaxy (S*b*) and even NGC 205 (E5)? Within this sequence the masses vary within a range of about 1 to 200; the densities, within a range of 1 to 50; and the gas content, within a range of about 100 to 1 (*64*). We cannot see any reason whatsoever why, under such diverse conditions, there should have originated everywhere the same relative abundance ratios for all the heavy elements and the same maximum metal abundance, to within an error of less than 50 percent.

4) In connection with the proposed formation of the galactic disk by collapse out of the halo, we further consider a mechanical argument. We may expect the whole system to retain approximately cylindrical symmetry during the collapse of the disk. Therefore, for any star, the component of its orbital angular momentum parallel to the axis of rotation (and collapse) must be conserved all through the evolution of the galactic system.

Recently Oort (*65*) investigated the velocity component in the direction of galactic rotation for a stellar population of extreme halo II character—namely, metal-deficient RR Lyrae variables. It turns out (*66*) that their orbital angular momentum per mass unit is more than 8.3 times smaller than that for the disk population and the spiral-arm population I in the neighborhood of our galaxy. For any reasonable mass distribution and velocity distribution in the galaxy, the angular momentum per mass unit is therefore considerably smaller in the halo than in the disk. This raises severe doubts as to whether an origin of the galactic disk by partial collapse of the halo is dynamically acceptable.

5) Finally I should mention that metal-rich and metal-deficient stars (should we still say stellar populations?) occur in the highly chaotic system of the Magellanic Clouds as well as in structureless elliptical galaxies like NGC 205. Metal deficiency thus appears to have, in general, nothing to do with the differentiation of halo and disk.

In view of all these arguments, it seems almost impossible to maintain the conventional theory of the early evolution of the galaxy.

How might the early evolution have proceeded? I can only propose a quite tentative hypothesis, one that in some respects approaches ideas which—in rather different context—were advanced years ago by Ambarzumian (*67*).

The observation that the vast bulk of cosmic matter in very different galaxies consists of the same mixture of hydrogen, helium, and all the heavy elements points toward a universal origin of that mixture (Table 1). Whether we should return to some improved form of the Lemaître-Gamow theory or whether a more "local" theory may still be a possibility may remain an open question for the moment.

The low angular momentum of the halo, its almost spherical shape, and its highly excentric orbits point toward the idea that it originated out of the central part of the already flattened protogalaxy. The mixture of elements which is characteristic of the halo stars, together with their orbital characteristics, could then be explained by assuming that in the protogalactic center there happened a gigantic explosion, similar to those observed in radio galaxies and quasars. The existing "normal" matter was mixed with debris of the explosion, consisting of hydrogen and helium in a ratio of about 6 to 1, without heavy elements. In this connection it is interesting to note that, according to Peebles (*62*), Wagoner, Fowler, and Hoyle (*63*), Tayler (*61*), and others, under a considerable variety of circumstances a large cosmic explosion is quite likely to produce just such a mixture of elements.

Quite apart from more detailed ideas about the early history of the galaxy, we have noted that almost all the heavy elements were already present at its beginning, or were produced during a short interval near its beginning. Therefore, the heavy elements which we have on the earth and in meteorites should be of practically the same age as the galaxy. Since we believe (from well-known arguments) that the terrestrial and meteoritic uranium isotopes U^{235} and U^{238} cannot be older than about 7×10^9 years, we expect this to be also an upper limit for the age of the galaxy. A few years ago a cosmic time scale of 10^{10} or even 2×10^{10} years was favored by most astronomers. More recent work by Iben (*68*) and others has given clearer insight into the importance of the assumptions underlying calculations on stellar evolution, especially in the oldest globular and galactic clusters. Taking into account the evidence coming from the spectroscopic analysis of various cosmic objects, we probably should—and in fact can—accept a time scale of $\sim 7 \times 10^9$ years as one of the boundary conditions for the selection of possible models for stellar evolution and for relativistic world models.

Conclusion

Spectroscopic determination of the chemical composition of stellar atmospheres and of gaseous nebulae leads to the following conclusions.

1) During the evolution of more than 95 percent of the stars, the abundance distribution of the elements in their atmospheres has not been affected by the energy-producing nuclear processes in the stellar interior. The abundance distribution is that of the interstellar matter out of which the star was formed.

2) In the relatively few pathological" stars, the matter which we observe now in the atmosphere has been strongly affected by the energy-producing nuclear processes in deeper layers.

3) Otherwise, in all stars of our galaxy and in other galaxies differing widely as to mass, mass density, gas content, and so on, the relative abundance ratios of all the heavier elements (from carbon to barium and beyond) and probably also the helium-hydrogen ratio are the same.

4) The ratio of all the heavy elements ("metals") to hydrogen (and probably to helium) is reduced by factors of up to 200 or 300 in some stars of the halo population II of our galaxy and in similar stars of galaxies having a different structure (of the Hubble type). However, in all galaxies the maximum ratio of the heavy elements to hydrogen in the "normal" stars reaches the same universal value (Table 1).

5) In our galaxy the component of the orbital angular momentum parallel to the axis of rotation (per mass unit) is considerably smaller for the extreme halo population II than for the disk population.

These observations seem to require a revision of our present ideas about the origin of the elements and the early evolution of the galaxy. Most probably the "standard mixture" of elements originated by "mass production" at a very early stage in the evolution of the universe. The galactic halo may have originated, early in the history of our galaxy, from a gigantic explosion in the galactic nucleus—an explosion which produced only hydrogen and helium, in a ratio of 6 to 1, mixing them with the already existing "standard matter."

The age of the galaxy and of the universe cannot exceed that of the heavy elements, and therefore is limited to about 7×10^9 years.

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