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ON THE CHEMICAL COMPOSITION OF THE MILKY-WAY OBJECTS

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Abstract. A review of the chemical composition of our Galaxy - the Milky Way - is presented. In addition to the well-known facts, such as dominance of hydrogen and helium over the heavy elements, etc, it should be emphasized that undoubtedly there is a correlation between the fraction of the heavy elements and the spatial distribution. On the other hand, though it seems possible, the existence of a negative gradient (decrease) in the mean metal fraction, for any subsystem of the Milky Way, is still uncertain. From this may arise additioinal complications concerning, say, the age-metallicity relation.

1. INTRODUCTION

It is clear that the first concepts and ideas concerning the "constituents of our world" belong to remote past. Since the scope of the present article is rather limited, a, practically, unavoidable historical review can be started by mentioning the discoveries of the XVIII century which laid the foundation to the modern chemistry: works of Lomonosov, Priestly, Lavoisier and others. In the following century - the XIX - the very modern concept of atoms and molecules (Dalton) is already mature. As very well known, the former ones appear as the smallest quantities of what is known as a *chemical element*, whereas the latter ones have the same meaning for what is known as a *compound*. The middle of the XIX century is the time of coming into use of the chemical symbols and chemical formulae. With it, even some organic compounds had become known.

Thus the role of the elements was already clear, it remained to find an *order* among them. This was done by D. Mendeleev who introduced a grouping of chemical elements taking into account their chemical properties and increasing atomic weight - nowadays referred to as *the periodic table*. In the periodic table each element is characterised by two numbers - the atomic number and the atomic weight. They were explained by the physics of the XX century: since the main part of each atom is its nucleus, the former number is equal to that of protons in the nucleus, whereas the latter one is equal to the total number of particles (protons and neutrons). According to this interpretation the essence of a chemical element is the nucleus of its atom (more precisely the nucleus of a given atomic number, one should also think of isotopes), once it was formed, it just remains to add the electron shell and we have a chemical element since any quantity of a chemical element is a mere ensemble of its atoms. This standpoint has been fully confirmed by the modern nuclear physics - the phenomena of radioactivity, fission, fusion and finally the production of artificial nuclei (elements) in a laboratory.

2. CHEMISTRY AND ASTROPHYSICS: COSMICAL EVIDENCE CONCERNING CHEMICAL ELEMENTS

Though at first glance it may seem far from chemistry, astrophysics has given an important contribution to the history of chemical elements. It has explained how the elements (nuclei of their atoms) were formed. The stars, those distant celestial light sources, are in reality factories of chemical elements. Probably the story of compounds has also its origins in the universe, perhaps life, itself, originated somewhere far from the Earth. These are, of course, intriguing questions, but their consideration is beyond the scope of the present article. The first thing to be indicated here concerns the observational evidence of the chemical composition of stars and celestial bodies.

No doubt, there are two ways of obtaining evidence on the chemical composition of celestial bodies: the direct way by using the meteoritic material and the indirect way based on astronomical observations. Trimble (1996) in her review paper mentions works from the late XIX century where the meteoritic material was studied. On the other hand, it is very well known that in the early XIX century the dark lines present in the solar spectrum and also, in the spectra of other stars, were indicated by Fraunhofer. The further progress in physics in the same century (works of Doppler, Kirchhof, Bunsen, Stephan, Boltzmann, etc) enabled a correct interpretation of stellar spectra. It became possible to determine the physical conditions in the stellar photospheres and atmospheres and also, the presence and abundances of various chemical elements (in recent times the same was archived for the case of compounds). The possibilities of modern instruments allow the obtaining of very fine spectra and thanks to the progress in quantum mechanics detailed calculations for the purpose of giving their explanations are now performable.

The first important result of these studies is that *qualitatively* there is no difference in the chemical composition of the Earth and beyond it. In other words the same non-artificial 92 elements have been found on both the Earth and celestial bodies. It may be noticed for curiousity that helium was first discovered on the Sun, to be confirmed on the Earth afterwards.

The second important result is that *quantitatively* the chemical compositions of the Earth and nearby celestial bodies (in particular, the Moon and the terrestrial planets) on the one side and for, say, the stars, including the Sun too, on the other side, are very different. Since the subject of the present paper concerns the chemical composition throughout our own Galaxy, the Milky Way (in further text MW), there is no need to mention the chemical composition of other classes of objects (e.g. comets); it is sufficient to say that the chemical composition of the Jupiter-like planets is like that of stars.

3. ELEMENTAL ABUNDANCES IN THE MILKY WAY

During the first half of the XX century spectra of many stars were treated and in this way became available to further analyses. Some of the important moments in the history of obtaining first elemental abundances for stars of MW are related in Trimble's (1996) review. Therefore, any interested reader is referred to it. Here, only an important plot will be presented (Fig. 1). What can be noticed from it is a few strong peaks. The first one concerns the two least massive atomic nuclei - proton and alpha-particle. The other ones are less prominent, but their existence obtains a full explanation in branches of modern astrophysics, such as, above all nucleosynthesis.

As the principal conclusion it will be said that the chemical composition of the Milky-Way stars is dominated by hydrogen and helium. In addition, the former, as the element with smallest atomic weight, is also dominant in the interstellar matter and the situation is practically the same in other galaxies. Therefore, it is not difficult to understand why the chemical composition of a typical star is most frequently given with three quantities only: X (percentage of hydrogen), Y (percentage of helium) and Z (percentage of all other elements, in stellar astronomy traditionally referred to as metals); these quantities are usually mass fractions. As a quantitative example one may mention the case of the Sun. The corresponding amounts for our star are (Gehren, 1988): X is between 70% and 77%, depending on the value assumed for the helium fraction, which is between 21% and 28% and, consequently, Z is equal to 2%.

The example of the Sun shows that there is a serious helium problem, i.e. the problem is to estimate its mass fraction correctly. Fortunately, the same example also shows that the helium problem affects the estimate of the hydrogen mass fraction only, whereas that concerning the metals remains unaffected. However, to studies of the chemical composition in MW in most cases the quantity Z is of highest interest. In such a situation one determines the relative abundances of metals, i.e. the ratio of number of atoms for a given metal to hydrogen. However, there are 90 metals, therefore to obtain such an information for each of them and for a sufficiently large number of MW objects requires much time. Besides, the best solution is to compare the relative abundance for a given object of MW with that characterising a "standard" object, say the Sun.

So one introduces a new dimensionless quantity, known as *metallicity*. It is defined as the Briggs logarithm of the relative-abundance ratio taken for a chosen metal of a given object of MW and the Sun. The data of such kind have been obtained for many objects of MW (stars and star clusters). They indicate that individual deviations in metal abundances can appear, i.e. inside Z not all the metals have constant rates for all objects of MW. However, a general trend is noticed - that Z can be significantly different depending on what objects are considered. Therefore, in view of the difficulties mentioned above as a practical solution one accepts to choose one metal as "representative". Then the metallicity definition is applied to it. The chosen metal is iron. The reasons are the following. First, iron (see .s.) is among the most abundant metals. Second, its lines are dominant in the stellar spectra suitable to analysing for the purpose of obtaining the information concerning the metal abundances, say spectral types between B and K (e.g. Marochnik and Suchkov, 1984 - p. 33), which means that the data on the iron relative abundance can be obtained for a very high number of MW objects. Finally, in the case of iron the relative abundance can be obtained more accurately than in the case of other metals (Gehren, 1988). Therefore, in the further text the notion of metallicity will be related to iron and, consequently, the corresponding designation will be $[Fe/H]$. When the metallicity for an MW object is known, its metal fraction Z can be found approximately as $Z = Z_\odot 10^{[Fe/H]}$.

The task of galactic astronomy, or more precisely of galactic statistics, concerning the chemical composition is to study the metallicity distribution of galactic objects.

4. THE BASIC FEATURES OF THE METALLICITY DISTRIBUTION IN THE MILKY WAY

Any statistical research in MW should, certainly, take into account the fact, of which we became aware with the pioneering works of Baade (e.g. 1944), that the structure of our Galaxy is composite. As well known, Baade introduced the concept of *populations*. The stellar populations have been very often mentioned in connexion with *subsystems*, even identified with them. The present author's opinion is that these two notions should, nevertheless, be distinguished. The subsystems (in galactic astronomy introduced by Lindblad as early as 1930-ies) concern, above all, the spatial distribution, whereas the populations involve the matter, whereby the concept originator (Baade) took into account first of all the physical properties. Therefore, the populations may be understood as the content of different subsystems. It should be also noticed that the populations are very often thought to have discrete character. As an example one can mention the idea of Suchkov and his co-workers generally presented in Marochnik and Suchkov (1984) and also in journal articles (e.g. Marsakov and Suchkov, 1977), according to which the objects of MW are closely grouped around the mean metallicities. The scatter within each of these groups is largely due to the errors rather than to be intrinsic. Later studies seem to be not in accordance with this concept. Therefore, the best choice is to accept as the starting point the well-known division of MW into classical subsystems, such as the the disc, the halo, etc. This division is based on the space distribution, or more precisely, on kinematical properties. On the other hand, there is no doubt that the kinematical properties are correlated with the physical ones. According to Sandage (e.g. 1986) among the physical properties the most important are metallicity and age.

Thus the statistics of MW, if the evolutional problems are not discussed, cannot avoid the correlation between metallicity and spatial distribution, i.e. kinematics. Among the classical subsystems of MW or, more precisely, those composed of the visible matter the three most important ones are the bulge, (thin) the disc and halo (e.g. Kulikovskij, 1978).

Therefore, any statistical research concerning the metallicities has to consider the objects of different subsystems separately. Here, it should be, certainly, emphasized that for an arbitrary galactic object under study, or a group of them, it is not easy to indicate the subsystem to which it belongs. Besides, for different subsystems different interpretations are possible. Therefore, it is not surprising that one finds different results for the metallicity distribution within a given subsystem only because not the same objects are treated. Clear and exact limits for the purpose of separating different subsystems cannot be established, among others because the metallicity distribution, itself, is also used as a separation criterion.

5. THE METALLICITY DISTRIBUTION IN THE BULGE OF THE MILKY WAY

The data concerning the bulge objects are in favour of its high metallicity . However, at this point one should be careful because the basic criterion for classifying the observed stars to belong to the bulge is their position, or very often their direction (the famous Baade's window). On the other hand the number density of the other subsystems is also expected to increase towards the galactic centre, hence many stars identified as bulge ones in reality may belong to other subsystems. This controversy should be, certainly, connected to the general bulge question, because, indeed, there are different concepts as to what, generally, a bulge of a galaxy (including the galactic one, also) could be (e.g. Freeman, 1987; Frogel, 1988). The present author will consider the bulge question in this text again, while now the state of matter concerning the disc and halo will be presented.

6. THE METALLICITY DISTRIBUTION IN THE DISC OF THE MILKY WAY

The disc has been often considered as the most important subsystem of MW not surprising at all observing that MW is a typical spiral galaxy, i.e., its light, is dominated by its disc. In addition, it seems doubtless that the Sun is a disc object. There is another class of objects for which there can be hardly any doubt that they belong to the disc. These are open clusters. Today more than 1000 open clusters are known, but for many of them the necessary data are missing, often even the heliocentric distance (e.g. Nagl, 2000). A brief inspection of the data is enough to indicate that the sample of open clusters is incomplete since among the known ones a strong paucity is noticed when, for instance, one goes towards the galactic centre. The reason is probably because they are very near the galactic plane and in the central parts the detection conditions are bad. In spite of all of this their metallicity distribution is characterised by a strong peak near the solar value ($[Fe/H] = 0$ - Fig. 2). Besides, as seen from the Fig. 1, it is not symmetric. In principle, the circumstance that in disc objects (or suspected as such) there are not of them with metallicities approaching $[Fe/H] = -1$ seems to be well known. This value has been even indicated as the bordering one for separating the disc from the halo.

7. THE METALLICITY DISTRIBUTION IN THE HALO OF THE MILKY WAY

The halo of MW has been always of special interest. Its objects are assumed as very old, perhaps with the highest age in MW. Among them a special attention has been traditionally paid to globular clusters. This is not surprising if borne in mind that their sample is, most likely, the most complete in MW. Also for almost all of them the heliocentric distances are known. The metallicity distribution (Fig. 2) is very interesting. It is, as established by Zinn (1985), bimodal. If, having regard to the comment from the previous subsection, only those with $[Fe/H] < -1$ are accepted as true halo objects, then their metallicity distribution is rather well described by a Gaussian curve centred on $[Fe/H] = -1.6$, where almost 70% of them are within $[Fe/H] = -1.9$ and $[Fe/H] = -1.3$. As for the "metal-rich globular clusters, those with $[Fe/H] > -1$, they also show a strong peak, however considering that they are much less numerous than the "metal-poor" ones, one should be careful in the interpretation. Namely, it cannot be excluded that their enhanced concentration between $[Fe/H] = -0.7 - -0.5$ is accidental (Nagl, 2000).

What is sure now is that the halo is the most metal-poor subsystem in MW. The metallicity data mentioned above confirm this statement clearly. This is the reason why the halo is so interesting. The lowest metallicity established for an MW globular cluster is -2.24 (...), whereas the corresponding value for the case of halo field star is about -4. It is not clear what could be the reason for such a discrepancy, perhaps extremely metal-poor globular clusters dissolved very early in the history of MW (e.g. Gehren, 1988). In studying halo field stars the problem of relating a particular star to the halo is somewhat problematic.

There is much in common in the metallicity distributions of the globular clusters and halo field stars. It even seems that there are halo field stars of almost the solar metallicity (Mc William, 1997). If this statement is correct, then it becomes more probable that the metal-rich globular clusters really belong to the halo. It is curious to notice that, though the metallicity distributions of the field stars and globular clusters, of course, do not coincide (one is to bear in mind, for instance, the lowest metallicities found in both groups), the mean metallicity for the former ones is also about -1.6 (Mc William, 1997), just as in the case of globular clusters (metal-poor, but they are much more numerous in MW).

Thus regardless of all unsolved and unexplained questions, such as: are all individual objects correctly identified with the corresponding subsystem? do the exceptionally metal-rich globular clusters (above the solar abundance, found just a few) also belong to the halo, or perhaps they are bulge objects? etc. - It is certain that the halo of MW is significantly metal-poorer than the disc.

8. METALLICITY GRADIENT IN MW

In the above text one has considered the metallicity distribution of individual objects on the basis of their identification with particular subsystems, where their galactocentric positions have not been taken into account. It should be noted that in galactic astronomy, as generally in stellar astronomy, stellar systems are considered as fluids. In view of this it is possible to study the dependence of the average metallicity (and of other statistical parameters) on the galactocentric position. However, in oder to be able to solve this problem correctly one should have for many galactocentric positions a large body of data, i.e. a large number of galactic objects situated in the immediate surroundings of these points with known metallicities. It is clear that this condition is fulfilled for one point only - the galactocentric position of the Sun. Of course, in such studies galactic objects belonging to different subsystems require separate treatments.

What remains to be done is to compare the metallicity distribution within a well-defined sample of galactic objects to the spatial one for the same sample. In such a way it is possible to get an insight in the change of the mean metallicity with the galactocentric position. As very good tracers for such studies appear star clusters. Then one can easily form samples with very reliable distances and, besides, the star clusters (especially globular) are very bright and their samples cannot be strongly biased for lack of completeness. On the other hand, the two known types of star clusters are representatives of two different subsystems: the open ones belong to the disc, whereas the globular ones belong to the halo. It is not clear whether a part of globular clusters, with a relatively flat spatial distribution, belongs to the disc or to the halo, or, perhaps, these clusters belong to the thick disc. In the literature they have been chiefly considered as disc objects following Zinn (1985). However, there are different points of view (e.g. Nagl, 2000) according to which they, nevertheless, belong to the halo.

Thus a group of objects of MW with known metallicities and distances is analysed by means of a plot, say metallicity versus galactocentric distance (or distance to the axis of galactic rotation, resp. distance to the galactic plane). A trend is thereby, determined, usually applying the least squares, and, finally, one obtains the dependence of the mean metallicity on the position (distance used). Of course, such a treatment results in a linear trend and the coefficient multiplying the distance is referred to as the *metallicity gradient*. Since the bulge is small (compared to disc and halo), its gradient is not established. As for the other two subsystems, the corresponding metallicity gradients have been found. As could be expected, they are negative. With regard to what was said in the preceeding paragraph the most suitable samples for this purpose are those containing star clusters. So the metallicity gradient for the disc is approximately equal to -0.1 dex kpc $^{-1}$ (Friel, 1995). However, a gradient determination based on open clusters has also limitations because the very inner disc parts are practically free of open clusters. For this reason any extrapolation of this result towards the galactic centre is uncertain. In the case of the halo, due to its large extension perpendicular to the galactic plane, one frequently determines two metallicity gradients: in the galactic plane (radial) and perpendicular to it (vertical); of course the alternative possibility is to assume spherical symmetry for the halo and then there is only one gradient value. As already said, the obtained amounts are negative (no matter which gradient is used), but in the studies based on globular clusters most frequently applied approaches are without linear trends (e.g. Alfaro et al., 1993). As a consequence, there is no general value as in the case of the disc. Therefore, the mean metallicity in the disc and halo of MW is, most likely, a decreasing function of the galactocentric distance (to the rotation axis, resp. to the galactic plane), but the rate is rather small. The present author has not been able to find in the literature estimates concerning the spatial variation of other elements of metallicity distribution (e.g. dispersion).

9. CHEMICAL EVOLUTION OF MW

To consider the chemical evolution of a stellar system, in the present case MW, means to study the metallicity dependence on time. As said above, the available data on the chemical composition of individual stars concern their upper layers. On the other hand, the stars are "factories of chemical elements" (see preceeding sections) and, as a consequence, their chemical compositions are subject to changes in time. However, this change or, more precisely, the enrichment in heavy elements, takes place in the stellar interior. Because of this the observable chemical composition remains almost unchanged with time. In this way the most important relationship established in the studies of chemical evolution becomes that between age and metallicity. In general one may expect the oldest stars to be the most metal-poor because the processes of ejecting their matter can enrich with metals (and helium) the interstellar matter. It is understandable that stars born later on can then be more metal-rich.

In the preceeding sections it was said that extremely metal-poor stars (with no metals) have not been discovered. It is also said that the halo is substantially metal-poorer than the disc. The age determinations are in favour of the halo being also substantially older than the disc. When mentioning age determinations, it should be said that they are much more easy and, consequently, much more reliable for star clusters, where one uses the colour-magnitude diagram, than that of individual stars. In the latter case one applies very often indirect criteria, say, the kinematics, especially for the disc. However, even for a star cluster, an age determination has not been deprived of difficulties considering that it has not been independent of the metallicity value assumed for the cluster (e.g. Marochnik and Suchkov, 1984 - p. 58).

The general situation concerning the age-metallicity relationship is rather controversial. In the case of the halo the metallicity spread is large, but the corresponding age spread is not, it is even possible that, for instance, the metal-poor globular clusters are almost co-eval. On the other hand, in the case of the disc there is an almost general agreement that the age spread attains 10 Gyr (e.g. Friel, 1995), but it is not certain if there is any correlation between age and metallicity. Twarog's (1980) finding of an apparent gradual enrichment of the disc in the heavy elements has become questioned, especially after using the data on the old open clusters where their relative paucity in the heavy elements can be alternatively interpreted by taking into account their large distances to the galactic centre in view of the negative abundance gradient mentioned above (e.g. Friel, 1995). A curious thing to be mentioned is that even the same paper can have different interpretations in different review papers, for instance, according to Friel (1995) the results of Edvardsson et al. (1993) are in favour of no age-metallicity relationship for the disc concluded on the basis of studying the data concerning old open clusters, but according to McWilliam (1997) these results are not against Twarog's (1980) age-metallicity relation. Some new metallicity determinations for young open clusters (e.g. Sung et al., 2002) give results which might be expected from Friel's (1995) disc metallicity gradient obtained on the basis of the data for old open clusters, i.e. against a strong age-metallicity relation. To all of this one should also add that the bulge, thought to be significantly rich in the heavy elements (see preceeding sections), seems in general to have a significant age (e.g. Frogel, 1988).

Two best known concepts concerning the general evolution of MW are, certainly, those of Eggen et al. (1962) and of Searle and Zinn (1978). According to the former one the matter of the galactic disc was subject to a rapid and strong vertical collapse to form a very flattenned structure as known nowadays. In the scenario of the latter paper the galactic evolution becomes more chaotic. In it an important role belongs to transient high-density regions which are places of formation of stars and star clusters, whereas the gas lost from these protogalactic star-forming regions was eventually swept into the disc.

The chemical evolution has been studied in detail for the case of the disc. The reason is the large body of data for the solar neighbourhood allowing the study, for instance, of the change in the local (at the Sun) surface density of the disc contributed by all kinds of matter (stellar and interstellar). In Twarog's (1980) paper one finds a short discussion concerning various models describing variations in time of parameters characterising the solar neighbourhood (e.g. initial mass function, star formation

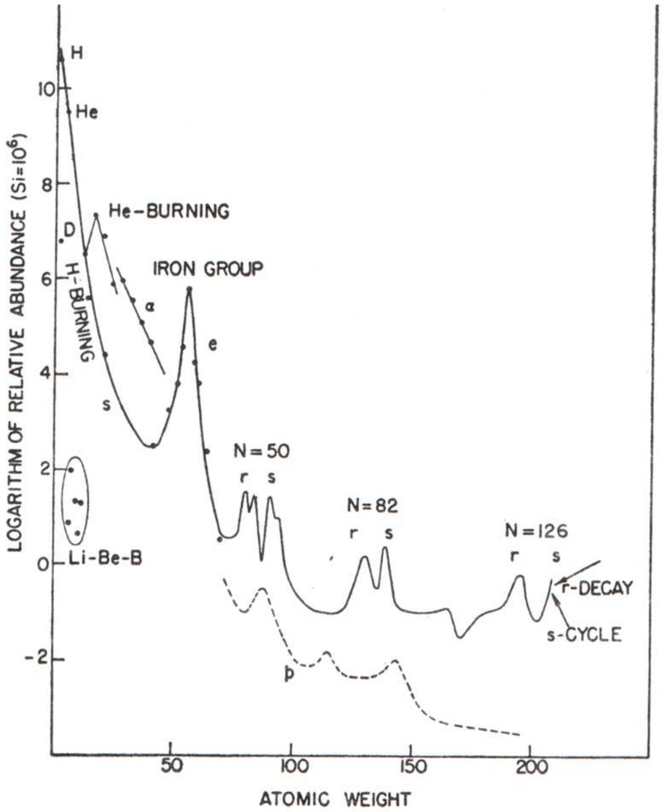

Fig. 1: The abundances of various nuclei according to Trimble (1996).

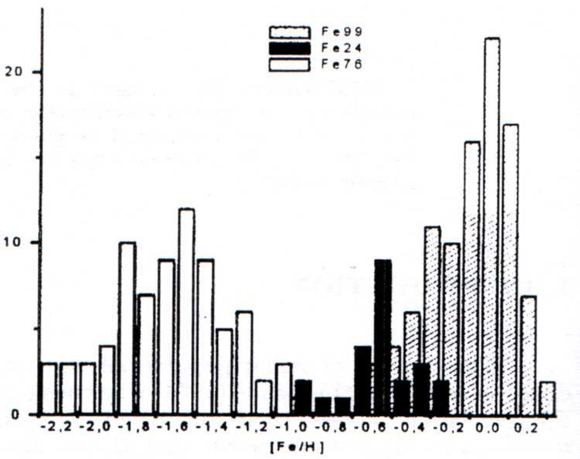

Fig. 2: The metallicity distribution for star clusters in MW - G76 "metal- -poor" globulars, G24 "metal-rich" globulars, G99 open clusters.

rate, etc.). These models can be compared to the results obtained by analysing the observational data, such as, for instance, Twarog's (1980) age-metallicity relation. Of course, a successful comparison requires the used data to be both sufficiently reliable and comprehensive. If this requirement is not fulfilled, then the consequence will be contradictory interpretations, as, for instance, that the disc has been gradually enriched in the heavy elements, i.e. it was subjected to a rapid enrichment which occurred long ago.

10. CONCLUSION

No doubt, in general, the chemical composition of MW is similar to the composition of other galaxies and the results are as could be expected on the basis of the Big-Bang theory. On the other hand, there are observational facts still waiting for a reasonable explanation, such as the large scatter in metallicity for objects supposed to belong to the halo, the bulge problem, etc. Therefore, a future work on the treatment of the metallicity data is necessary.

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