Astro-Archaeology: Observations at La Silla of Some Old Halo Stars

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When, where and how were the heavy elements produced in the young Universe? Present theories say that it mainly happened in supernova explosions, but only accurate observations of very old stars can show whether this is true or not. Drs. Monique and François Spite from the Paris Observatory in Meudon recently started a study of very metal-deficient stars in the Galaxy to see if there are minor differences in the abundances of the individual metals, as predicted by theory. Here they inform us about the reasons for their observations and give some of the first results.

Like an archaeologist, who traces the history of mankind by analysis of fossils from different, more or less remote epochs, the astronomer can try to learn the evolution of the Universe by analysing old stars which were born when the Galaxy was young.

Element Synthesis in the Universe

It is generally believed that the observable Universe began in a cosmic explosion (the Big-Bang) of which a characteristic fossil is the 3°K radiation.

During the first few minutes of this Big-Bang was formed all the Hydrogen and the larger part of the Helium now present in the Universe. This gas condensed afterwards in huge clouds which in turn condensed into protogalaxies. In these protogalaxies, some material condensed into stars. The chemical composition of their atmospheres should be the same as the composition of the material formed in the Big-Bang: essentially Hydrogen, Helium and possibly a small amount of Lithium. In the core of these first-generation stars, the metals began to be synthesized through successive nucleosynthesis processes: helium burning, carbon burning, silicon burning (this last process, in particular, builds all the elements of the iron peak). When, at the end of their life, the stars exploded as supernovae, the produced metals were dispersed and mixed into the interstellar medium, ready to be included in the second-generation stars. These metals are called *primary metals*, i.e. metals built by first-generation stars.

It is an important fact that these stars apparently were unable to build all kind of metals. For instance, Barium is built through irradiation of iron seed nuclei by slow neutrons (the "s" process). Present theories show that during the evolution of a first-generation star, the slow neutron flux arises before the iron nuclei are formed. For this reason, Barium (as well as all other elements formed by the "s" process) is called a *secondary* element. If the mass of the first-generation stars were large, they must have been rapidly transformed into supernovae, and it is generally assumed that the young galaxy was quickly enriched in metals.

If some first-generation stars still exist at the present epoch, then they must be of small mass, in which case the evolution is indeed very slow. But small-mass, unevolved stars are statistically faint, and hard to detect: moreover, cool stars displaying only hydrogen lines in their spectra could be easily confused with reddened, hot stars. For all these reasons, it is not surprising that, up to now, no stars without metals are known. They are the "missing link" of astro-archaeology.

Second-generation stars are expected to contain a small amount of primary metals, such as Iron, and absolutely no secondary elements such as Barium. But these stars are now able to build small amounts of secondary elements in their core, while at the same time building primary metals. In the supernova phase, they inject all these elements into the interstellar material, which will later form the third-generation stars.

The third-generation stars are expected to display a large deficiency of all the metals and particularly of the secondary metals. Indeed the well-known star HD 122563 analysed by Wallerstein and his collaborators in 1963 is very metal-poor (300 times less metals than in the Sun) and it is still poorer in secondary metals such as Barium.

Observations of Halo Stars

This overdeficiency of Barium, sometimes called the ageing effect, was not always found in other metal-poor stars, so the situation was rather confused. We therefore decided to select and analyse a few very metal-poor stars, in order to get a better understanding of the chemical evolution of the Galaxy, and to corroborate the above outlined theory of nucleosynthesis.

When we began this work in Chile, we had on our side the clear sky and the good seeing of the La Silla observatory, as well as the advantage of a luminous and efficient spectrograph at the coudé focus of the 1.52 m telescope. At a dispersion of 12 Å/mm, its resolution is excellent. Against us were the relatively low efficiency of the photographic plates and the relative faintness of the stars. Later, the observations were continued with the échelle spectrograph and the Lallemand-Duchesne electronic camera: for a similar resolution, the accuracy is higher, and the necessary exposure times are much smaller. However these observations have so far been restricted to the blue spectral range.

We analysed three stars similar to HD 122563. This increased by a factor of two the number of stars which had been analysed in detail and which were metal-deficient by a factor of more than 200 relative to the Sun. Furthermore, B. Barbuy analysed a moderately metal-poor star (10 times less metals than in the Sun). Let us note here that the metal deficiency of HD 122563 is sometimes quoted in the literature with more extreme values (for instance 1/1000 of the solar metal content), but this is often due to the adoption of a different temperature scale. In order to compare on a sound basis the abundance of two stars, it is necessary to use the *same* temperature scale, and this is not always easy.

With the increase of the sample of very metal-poor stars that have been analysed in detail, the situation has become clearer. The main results of our study, which have some im-

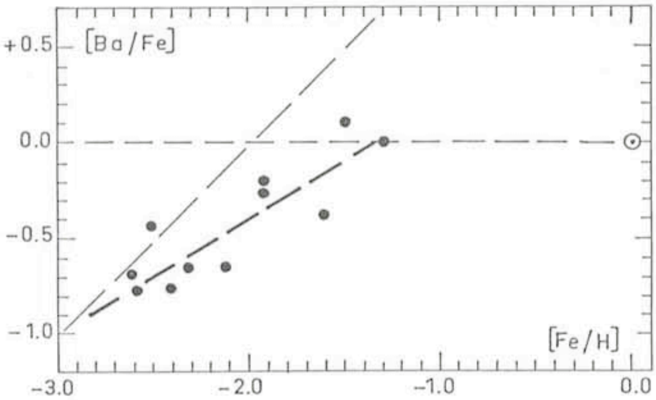

Fig. 1: *The [Ba/Fe] logarithmic ratio versus [Fe/H] (thin line: 45° line, thick line: mean relation).*

plications on current nucleosynthesis theories, are presented below.

1. Elements Built During the Carbon Burning Phase

Among the elements which are built during the carbon burning phase, it is possible to observe Aluminium, Sodium (Na) and Magnesium. The "pure explosive carbon burning theory" predicts that the elements with an odd number of neutrons are secondary elements. Accordingly, ^{27}Al and ^{23}Na should be more deficient in very old metal-poor stars than ^{24}Mg. But we were never able to find such an "overdeficiency".

On this point, our observations lead to a result that is different from the one obtained by R. Peterson. He undertook a similar study, at about the same time, with the échelle spectrograph at Mount Hopkins (Massachusetts, USA) and analysed metal-poor stars in the northern hemisphere. We first thought that this discrepancy was a result of differences in interpretation and not of the measurements. However, we undertook new observations and measurements of aluminium lines in our stars, also using échelle spectra. It seems that the new spectra confirm our first conclusion, that Aluminium is *not* overdeficient relative to Magnesium. We are at present working on this point.

Anyhow this result is not completely unexpected: Arnett and Wefel recently concluded that the explosive carbon burning is preceded by an hydrostatic burning of carbon. Following their theory, if carbon burning is even partially hydrostatic, odd elements like ^{27}Al and ^{23}Na can be built in first-generation stars (as primary elements) and no overdeficiency of these elements is then expected in metal-poor stars.

2. The "s" Process Elements

Figure 1 shows the behaviour of the logarithmic ratio [Ba/Fe] relatively to [Fe/H]. Let us recall the meaning of the classical notation:

$$[X] = \log (X\star / X_{\odot})$$

The stars which have a mean metal-deficiency of a factor 300 (relative to the Sun), i.e. [Fe/H] = –2.5, have a Barium deficiency 5 times more extreme (1500 times less Barium than the Sun). This Barium overdeficiency disappears when the iron deficiency is more moderate than [Fe/H] = –1.3, i.e. 1/20 of the solar iron content. The graph explains why some authors were talking about a Barium overdeficiency and others were not. It all depends on the level of iron deficiency.

Another element, mainly built by the "s" process, is also observable: Yttrium. We could establish (fig. 2) an overdeficiency of Yttrium, quantitatively smaller than the overdeficiency of Barium. This is in agreement with theory and gives some support to the present theories of the formation of the "s" elements.

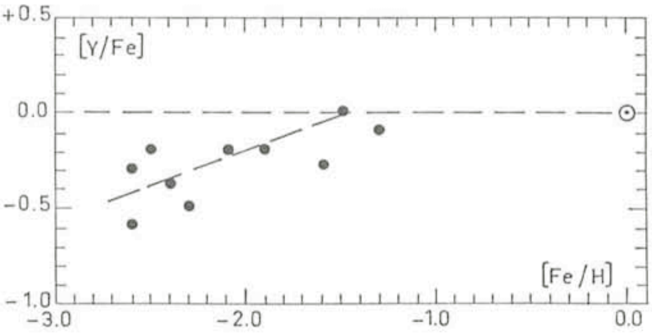

Fig. 2: *The [Y/Fe] logarithmic ratio versus [Fe/H].*

3. The "r" Process Elements

Europium is one of the very few "r" process elements which are observable in cool stars. The "r" process elements are formed by rapid addition of neutrons to iron peak elements. In contrast to the "s" process, a very high flux of neutrons is required. Europium belongs to the "rare earth" group, like Barium or Yttrium, but its behaviour seems very different. The deficiency of Europium is, within the measurement errors, the same as the deficiency of Iron. Europium is therefore a primary element; this induces us to think that it is built at the same time as Iron, during the silicon burning, when the star explodes as a supernova.

Future Work

This work does not yet give a complete picture of the chemical evolution of the Galaxy due to element building in stellar cores. We have begun with B. Barbuy an analysis of the abundances of Carbon, Nitrogen und Oxygen in these stars. It would be desirable to extend the sample, to find and to analyse other very metal-poor stars. An échelle spectrograph mounted at the Cassegrain focus of the 3.6 m telescope would provide us with the opportunity to analyse the chemical composition of the very old stars of the globular clusters. It would be possible to reach very distant stars which may possibly be even more extreme and represent a sample of the material of the remote past. Will it be possible to find stars of first or second generation? Will it be possible to observe differential abundances of metals in the stars of nearby galaxies? It is worth trying, since such observations would be a significant contribution to our understanding of the birth of the elements in the Universe.

Fig. 3: *A spectrum of the metal-deficient star HD 184711, obtained with the Echelle spectrograph at the 1.52 m telescope.*