GAIA, THE OLDEST STARS AND THE EARLY UNIVERSE

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ABSTRACT

The Extremely Metal-Poor (EMP) stars with [Fe/H]<-3 are the witnesses of the earliest phases of the evolution of our Galaxy; they were likely formed at an early cosmological epoch which corresponds to about z=5. At the present time, only hundreds of EMP stars are known but the Gaia mission is expected to detect thousands of them and will give very accurate distances and space velocities for these very peculiar objects. After a brief summary of what is known about these very old stars and what can be derived (like the nature and ejecta of the first supernovae, the age of the Galaxy etc) a short presentation is made of the improvements which can be expected in this field of research from the Gaia mission.

Key words: Galaxy: halo; Galaxy: evolution; Stars: metal-poor; Stars: abundances.

1. INTRODUCTION

The history of the formation and the evolution of our Galaxy is one of the main scientific topics of the Gaia mission. Gaia will help us in particular, to understand better the earliest phases of the evolution of our Galaxy. Many questions indeed remain unsolved: What was the IMF in a very-low metallicity environment? Does our Galaxy form from accretion of smaller systems? What was the nature and the ejecta of the first supernovae? etc.

The low mass stars have a life time larger than the Hubble time, and thus all the stars born shortly after the formation of our Galaxy (about 14 Gyrs ago) with a mass $M < 0.9\ M_{\odot}$ are still shining today. They are now G or K or M stars, dwarfs or giants and Gaia will observe a large number of these fossil stars. The atmosphere of these low mass stars has a very interesting property: its chemical composition does not change during the evolution of the star on the main sequence and on the Red Giant Branch (RGB). This is obviously a first approximation, lithium is known to be destroyed in the cool main-sequence stars and a mixing with the H burning layers affects C, N and Li abundances when the star ascends the RGB but the constancy of the chemical composition of the atmosphere of the low mass stars is at least a good starting hypothesis.

As a consequence, the chemical composition of the atmosphere of a very old star is a witness of the chemical composition of the matter at the beginning of the Galaxy. The abundances in very old stars are thus a fundamental tool to understanding the formation and early evolution of the Milky Way and to determining the characteristics of the first supernovae which have enriched the matter.

Moreover the analysis of the kinematics of these very old stars can help us to draw a picture of the early kinematic evolution of our Galaxy.

In Section 2 I will present the different surveys which, like Gaia, have among their objective the detection of EMP stars. In Section 3 we will see some examples of the results obtained recently from the study of the EMP stars. In Section 4 I will point out the future Gaia contribution to the understanding of the formation and the early evolution of our Galaxy.

2. HOW TO FIND THE OLDEST GALACTIC STARS?

Since the chemical composition of the atmosphere of a star reflects the chemical composition of the matter at the birth of the star, we expect that the atmosphere of a star born at the beginning of the Galaxy reflects the Big Bang nucleosynthesis: it must be made of H, He, Li, and no metals. The successive supernovae enrich little by little the matter and thus metallicity is generally taken as a criterion of primevality.

The main (or secondary) topic of several surveys is the discovery of some more extremely metal poor stars in order to increase the limited sample now available. Since the strongest lines in the G and K stars are generally the H&K CaII lines in the blue, or the CaII triplet in the near infra red these surveys search for stars without (or at least with very weak) CaII lines in the blue or in the red.

2.1. The H&K Survey of Beers, Preston & Schectman

The survey of Beers, Preston & Schectman (Beers et al. 1992, see also Beers 1999) began more than twenty years

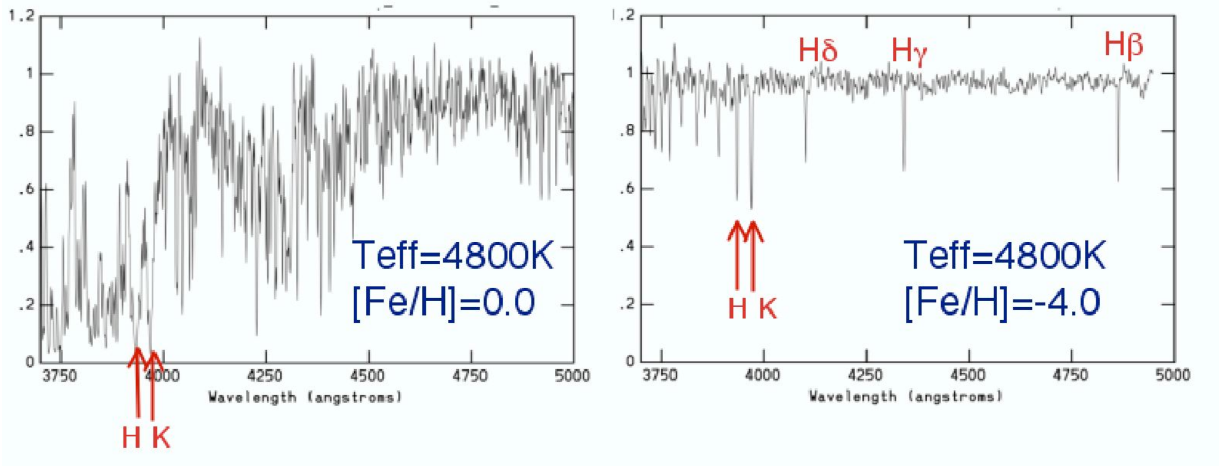

Figure 1. Comparison of the medium resolution spectra of two K stars: the first one is a Pop I star with a solar metallicity and the other one, CD-38 245, an EMP star with 10 000 times less metals than the Sun

ago. It was covering 6500 square degrees on the sky and the upper limit in magnitude was $\mathrm{B} \approx 16$. The metal poor stars were first detected by eye on objective prism plates (H&K lines very weak or not visible), then medium resolution spectra ($\mathrm{R} \approx 2000$) were obtained for the metal poor candidates to confirm their low metallicity and also to obtain a first estimation of this metallicity by comparing the intensity of the hydrogen lines to the calcium lines (Figure 1).

This survey has identified about 100 Extremely Metal Poor stars (EMP stars) with $[\mathrm{Fe/H}] < -3.0$. The most metal poor star found has a metallicity close to -4.0.

2.2. The Hamburg-ESO Survey (HES)

The HES survey is based on a similar technique. But all the objective-prism plates have been digitized and the selection of metal-poor stars is done by applying quantitative criteria to the features of the spectra. This survey is two magnitudes deeper than the H&K survey ($\mathrm{B} \approx 18$, and it covers a larger region of the sky. As a consequence the volume covered is increased by a factor of 8 relative to the H&K survey of Beers, Preston & Schectman.

In this survey about 200 stars with $[\mathrm{Fe/H}] < -3.0$ were identified, and the most metal-poor star found, HE 0107–5240, has $[\mathrm{Fe/H}] = -5.3$ (200 000 times less iron than the Sun). However this star is very peculiar, it is very rich in carbon, nitrogen and oxygen. Since these elements are the most abundant in the stars (after hydrogen and helium) the abundance by mass Z in HE 0107–5240 is only 100 times less than in the Sun ($[\mathrm{Z}] \approx -2$). On the contrary in CD–38 245 $[\mathrm{Fe/H}] = -4.0$ the most iron-poor star after HE 0107–5240 (Figure 1) $[\mathrm{Z}] \approx -4$.

Figure 2. Regions covered by the SLOAN and the SEGUE surveys.

2.3. The Sloan Digital Sky Survey and the SEGUE Project

The aim of the Sloan Survey was to use the ARC 2.5m telescope on Apache Point, New Mexico, to obtain calibrated images of 10 000 square degrees of the northern sky in 5 filters (u g r i z) and moderate resolution spectroscopy (R=1800) for 500 000 galaxies or quasars. As a by-product, 50 000 stellar spectra were also obtained in the interval 390 nm $< \lambda <$ 910 nm. The magnitudes of the stars are in the interval $14 < V < 22$. This survey covers on the sky a region opposite to the Milky Way (Figure 2); it will be finished by the end of 2005. But beyond 2005 the 'SEGUE' (Sloan extension for Galactic Understanding and Evolution) project will extend for three years the Sloan Survey to cover the Milky Way . It will become possible in particular to study the transition between the disc and the halo. This survey is expected to detect about 5000 EMP stars with $[\mathrm{Fe/H}] < -3$.

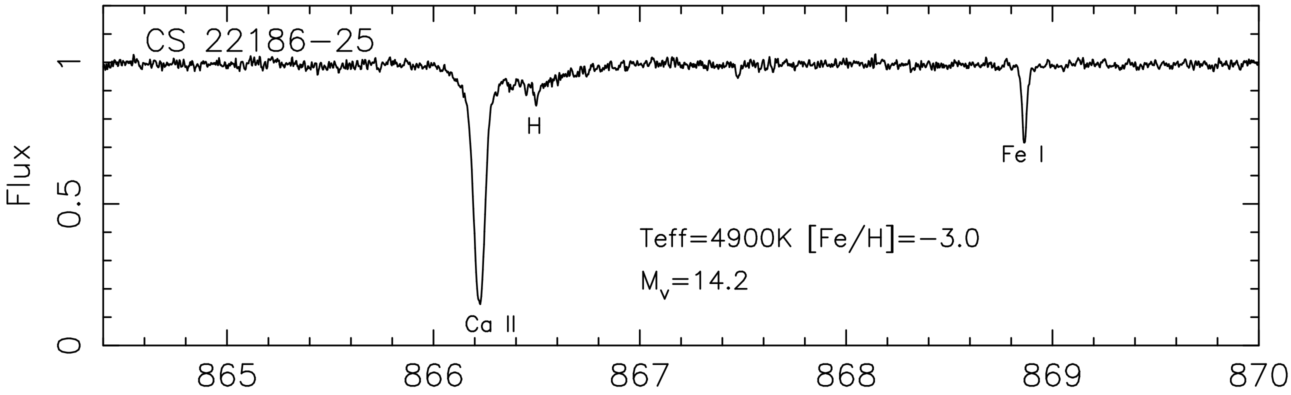

Figure 3. Spectrum of CS 22186-25 in the region of one of the red CaII line at 866.22 nm. The visual magnitude of the star is 14.2.

2.4. The RAVE project

This survey is described in detail in this volume (see the article by Ulisse Munari et al.). Let us recall however that the main topic of the survey is the measurement of stellar radial velocities to study the structure and the evolution of our Galaxy but RAVE will determine also the metallicity of the stars from the intensity of the red CaII triplet. Thousands of EMP stars will be thus detected by RAVE.

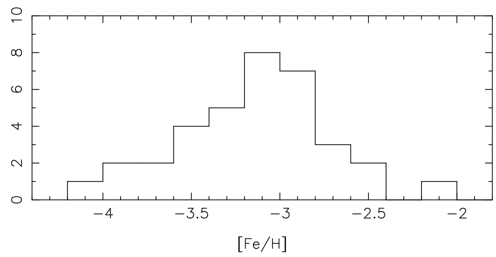

Figure 4. Histogram of metallicity of our sample of EMP giants

3. WHAT CAN WE LEARN FROM THESE VERY OLD STARS?

I will take here some examples from the first results of the ESO Large Programme ‘First Stars, First Nucleosynthesis’ (PI: Roger Cayrel). About 70 EMP stars (half dwarfs, half giants), selected from the H&K catalogue of Beers et al. (1992), have been observed with the high resolution spectrograph UVES at the VLT. The S/N ratio of the spectra was close to 200 and the spectral coverage was almost complete between 330 nm and 930 nm with a resolution $\mathrm{R} \approx 45\,000$. An example of the spectra, in the spectral region observed by Gaia, is given in Figure 3. The aim of this project was mainly to determine the characteristics of the first Supernovae and the age of our Galaxy. The analysis of the EMP dwarfs is underway, and thus I will speak only of the results obtained from the analysis of the EMP giants.

It is well known that many metal poor stars are carbon-rich like HE 0107–5240. Following Christlieb et al. (2001) there are up to 25% carbon-rich stars at $[\mathrm{Fe/H}] = -3$. In the selection of our sample we have avoided these stars because of the nuisance caused by the CH and CN lines in the measurement of weak lines. Thirty three stars can be considered as ‘normal EMP giants’ (not enriched in carbon) moreover two well known EMP carbon-rich stars were included for comparison. Most of the stars have a metallicity [Fe/H]< -2.7. The histogram of metallicities is given in Figure 4.

3.1. Abundance Ratios and Characteristics of the First Supernovae

The ratio of the different elements (like [Mg/Fe], etc) in the galactic matter has changed with time because these elements have been produced by different kinds of supernovae which have enriched the matter at different times. The massive type II supernovae have a very short life time ($<$ 0.2 Gyr), on the contrary the SN I have a longer lifetime (about 1 Gyr). At the very beginning of the Galaxy, only SN II had time to enrich the matter. Since the SN II eject a matter rich in α elements (like O, Mg, Ca) and poor in iron peak elements and since on the contrary, the SN I eject a matter poor in α elements and rich in iron peak elements, we expect that the ratio O/Fe at the beginning of the Galaxy should be higher than in the Sun. Thus for example we expect that $[\mathrm{Mg/Fe}]_{\mathrm{EMPstars}}$ >0.0.

In our sample of stars we could determine the ratios of the different elements, and it appears that at very low metallicity when $[\mathrm{Fe/H}] < -3.3$ the abundance ratios reach a ‘plateau’ (Cayrel et al. 2004). Some examples are given in Figure 5. It is then possible to define ‘mean abundance ratios’ typical of the early Galaxy and these ratios can be compared to the computed ejecta of the different types of supernovae.

In the composition of the EMP stars, we hoped to find the reflect of the ejecta of the VERY massive supernovae ($M > 100 M_{\odot}$) which could have, during their life, reionized the Universe at the end of the Dark ages. But

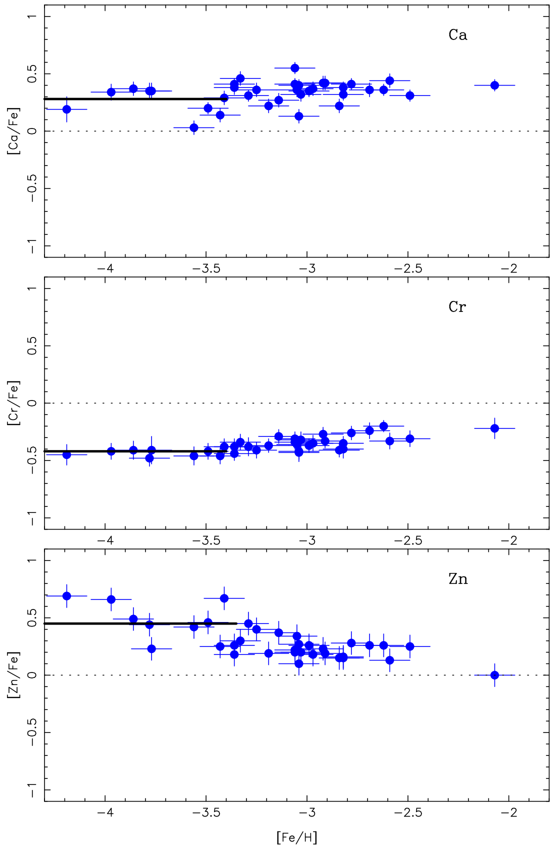

Figure 5. *[Ca/Fe], [Cr/Fe], [Zn/Fe] versus [Fe/H]. At very low metallicity the abundance ratios reache a 'plateau'. Note also the very small dispersion of the relation [Cr/Fe] vs. [Fe/H].*

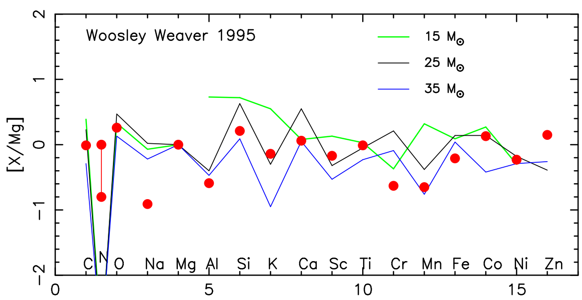

Figure 6. Comparison of the mean [X/Mg] values in the most metal-poor stars (dots) and the chemical composition of the ejecta of supernovae. Note that the ratios [X/Mg] have been preferred to [X/Fe] because in supernovae iron is formed very close to the frontier between the ejected layers and the remnant core and thus is very sensitive to the mass-cut. The agreement is rather good with supernovae in the range 15 to 35$M_\odot$.

Heger & Woosley (2002) predict in this case a very strong odd-even effect and an almost absence of zinc. These features are not at all observed since in particular [Zn/Fe] is clearly positive at low metallicity (Figure 5). The contribution of the very massive stars to the enrichment of the matter in the earliest Universe has been probably weak, maybe because the elements produced by these stars have been generally trapped in a black hole. Finally the best agreement is obtained with the predictions of Woosley & Weaver (1995) for masses of supernovae between 15 and 35 $M_\odot$ (Figure 6).

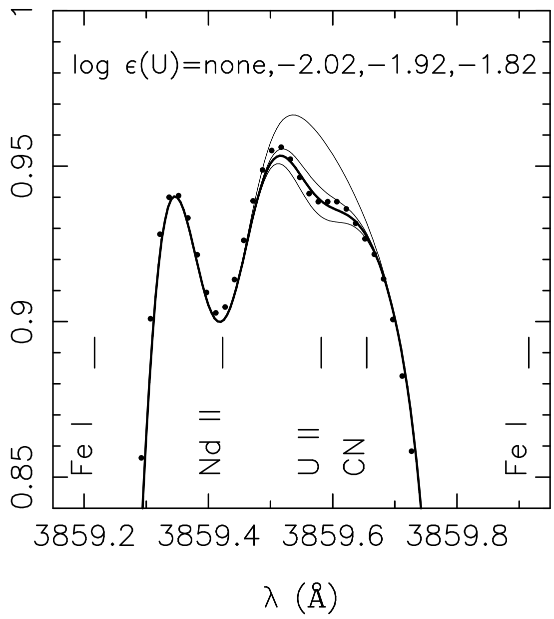

Figure 7. Spectrum of CS31082-001 in the region of the uranium line. Synthetic spectra are computed for different values of the uranium abundances. The best fit is obtained for $\log\epsilon(\mathrm{U}) = -1.92$

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3.2. Age of the Galaxy from the Abundance of the Radioactive Elements

A very rare sub-class of EMP stars has been very recently identified: these stars exhibit a very strong enhancement of the r-process elements relative to iron. This enhancement is so large that it becomes possible to measure the abundance of radioactive elements like Th or even in one case U (Figure 7). It is then possible to directly measure the age of the star if the initial abundance of these elements is known.

When possible, it seems that the best chronometer is the ratio U/Th, these elements have very similar nuclei so that their production ratio may be more reliably computed. From the comparison of the computed and observed U/Th ratio we derived for CS31082–001 an age of 14±2.4 Gyr (Cayrel et al. 2001; Hill et al. 2002). Since the star is extremely metal-poor ([Fe/H]= −3) this age must be very close to the age of the Galaxy itself and thus it is a very good approximation of the age of the Universe.

4. HOW WILL GAIA HELP?

4.1. Gaia will Discover More Bright Galactic EMP Stars

For the moment we know fewer than 300 EMP stars detected by the H&K or the ESO-Hamburg survey, but when Gaia is launched, from the SEGUE and the RAVE surveys, thousands of EMP stars will be known. Gaia will add thousands more EMP stars. This detection of new EMP stars remains important in particular if we want to study rare subclasses like the r-rich stars or to insure the trends of the abundance ratios towards the very low metallicity. Statistically only 1 star with $[\mathrm{Fe/H}] < -4$ is found for 200 stars with $[\mathrm{Fe/H}] < -3$.

Let us note however that neither Gaia nor RAVE will be able to measure the abundance ratios of these EMP stars; the lines other than the CaII lines are too weak. Complementary spectra will be necessary with high resolution spectrographs on very large telescopes, since most of the lines in these EMP stars are very weak and, on average, the stars are faint.

4.2. Gaia will Measure the Luminosity of the EMP Stars

In almost half of the EMP giants we studied, there is a mixing between the atmosphere of the star and the H-burning layer (Spite et al. 2005). This mixing alters the abundance of the light elements like C and N and it seems that in some cases sodium and aluminum are also affected. Since the luminosity of our stars was unknown $\log g$ was taken as a first order indicator of the luminosity. In Figure 8 we have plotted, for each star, $\log g$ as a function of the metallicity. The Red Giant Branch and the Horizontal Branch seem rather well defined and have been indicated by dashed lines. The unmixed stars generally belong to the low RGB and the mixed stars are on the horizontal branch or above. But the 'spectroscopic' $\log g$ value is rather uncertain and can be affected by NLTE effects (and also by the binarity of the star). It would be thus very important to know the true luminosity of the stars, in the same way as it has been done for less deficient stars by Gratton et al. (2000). And thus it would become possible to determine with precision at which phase of the evolution this mixing, which is not predicted by the standard theories, occurs.

4.3. Gaia will Check the Binarity of the EMP Stars

Duplicity is a key problem in astrophysics. It affects the measurement of the luminosity of close binary stars. It is thus very important to know whether a star is, or is not, a binary.

When an abundance anomaly is found, the binarity may suggest a mass transfer.

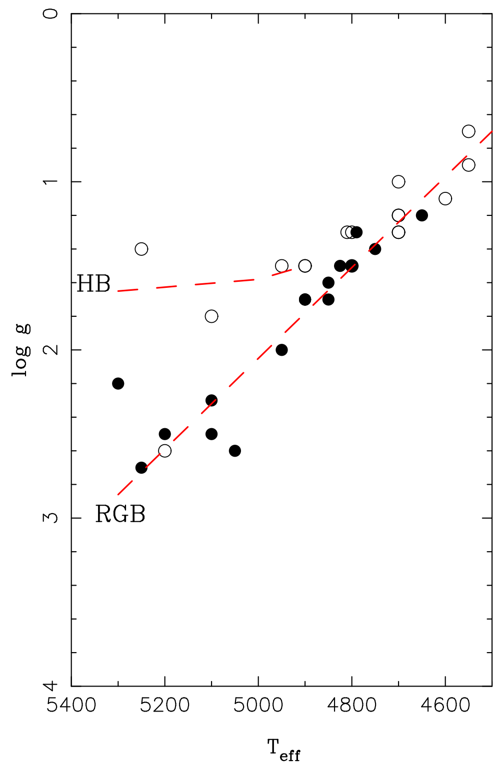

Figure 8. When for a sample of EMP giants, $\log g$ *is plotted versus* T_{eff}*, the stars draw a Red Giant Branch and a Horizontal Branch. The unmixed stars (filled circles) belong generally to the low RGB and the mixed stars are on the horizontal branch or above. It would be very useful to know the luminosity of these stars.*

Duplicity affects also the evolution of the stars in a way which is not clearly known.

Moreover, when the orbit and the orbital variation of the radial velocities are known it becomes possible to find the masses of the binary components. Gaia will determine the mass of a large number of EMP stars and maybe from these masses we can constrain the Helium abundance in the early Galaxy.

4.4. Gaia will Measure the Three Components of the Velocity of a Large Number of EMP Stars

Gaia will bring an extreme improvement in our knowledge of the halo formation. We will know indeed the parallax, the proper motion and the radial velocity of millions of stars and it will be thus possible to recover the 6-dimensional 'phase space coordinates' of metal-poor and extremely metal-poor stars and in particular the 3 components of the space velocity U, V, W.

To be brief there are two models in competition:

- The model of Eggen et al. (1962), where the halo is formed by a dissipative contraction on a short time scale. In this case we expect a relation between metallicity and kinematics.

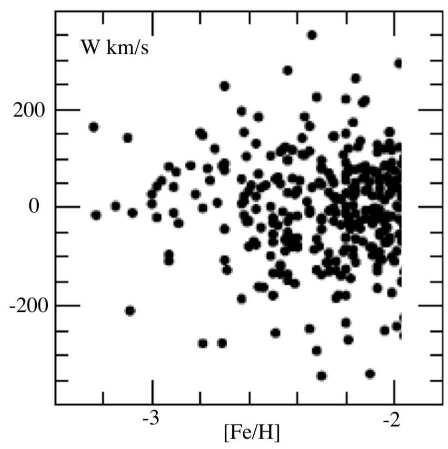

Figure 9. Distribution of the velocity component W vs. [Fe/H] for a subsample of halo stars following Chiba & Beers (2000). At very low metallicity, when [Fe/H]< -2.7 there is no more correlation between kinematics and metallicity.

- The model of Searle & Zinn (1978): where the halo is formed by accretion of fragments falling into the Galaxy. In this second case no relation between metallicity and kinematics is expected.

Some years ago Chiba & Beers (2000, 2001), tried to derive a model for the halo formation. They selected in the Beers et al. (2000) catalogue all the stars having available proper motions, radial velocities and distance estimate with $[\mathrm{Fe/H}] < -0.6$. Inside this sample they define a subsample with $[\mathrm{Fe/H}] < -2.2$ which likely represents a 'pure' halo component. This sample was selected without any kinematic bias. When for example for each star of the halo subsample, W (the component of the space velocity perpendicular to the galactic plane), is plotted versus [Fe/H] (Figure 9), there is first a trend of the velocity dispersion σ_W to increase when the metallicity decreases but when $[\mathrm{Fe/H}] < -2.7$, for the EMP stars, this trend disappears (at variance with the results of Norris (1994).

The absence of correlation between metallicity and kinematics is observed also for the other components of the space velocity U and V and even for the eccentricity of the orbits. The evidence offered in 1962 by Eggen et al. (1962) for a rapid collapse of the Galaxy, an apparent correlation between the orbital eccentricity of halo stars with metallicity, would be the result of a proper motin selection bias. Chiba & Beers (2000) conclude that the outer halo is made up from merging or accretion of sub-galactic objects such as dwarf type galaxies, wheras the inner part of the halo has undergone a dissipative contraction on relatively short timescales.

But from Figure 9 it is clear that this assertion is based on an extremely small number of stars. Even if we know at the present time more than 200 EMP stars their distance and thus their space velocity is generally unknown. There are only 8 stars with $[\mathrm{Fe/H}] < -3.0$ in the sample of Chiba & Beers (Figure 9). To derive a realistic picture of the early formation of the Galaxy it is necessary to gather the kinematics parameters of a statistically significant sample of extremely metal-poor stars.

5. CONCLUSION

The Gaia mission will produce an extraordinary data base which will completely revolutionize studies of the structure and evolution of the Milky Way. A large number of EMP stars will be detected and for these stars the distance, the luminosity, the position in the Galaxy and the components of the space velocity will be known. For the first time it will become possible to deduce a realistic picture of the formation and the earliest evolution of the Galaxy.

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