INTRODUCTION

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The opening session -- from right to left:
Dr. Beatriz Barbuy, President of the IAU Commission 29,
Dr. Johannes Andersen, the IAU Secretary,
Mrs. Wilma de Faria, Mayor of Natal,
Dr. Renan de Medeiros, President of the LOC,
and
Dr. Paulo Fulco, Heard of the Department of Physics-UFRN
representing the University

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The Light Elements and Their Evolution
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The light elements : what is known, what is controversial

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Abstract. The light elements are essential, because their primordial abundances are linked to the general parameters of the universe (at least in the Big Bang theory). Some of the light elements are fragile, and the interpretation of their abundances in stars requires a good knowledge of the stellar structure. The stellar abundances have to be known with a considerable accuracy, challenging the current level of representation of the stellar atmospheres. It is also difficult to reach accurate abundances in the gas : interstellar, H II regions, PN, intergalactic...

On the other hand, the fragile light elements are important probes of the stellar interiors, and their observation helps to the determination of reliable models, which in turn will improve the accuracy of stellar abundances. A part of this symposium is devoted to this probing aspect.

The talks (and many high quality posters) which build this symposium, cover all these aspects. I will try here to point out the controversial points and the reasonably well known facts. We expect from discussions, both formal and informal, a number of (eagerly awaited for) clarifications.

1. Introduction

Among the theories of the early evolution of the Universe, the Big Bang is currently the one which seems the less open to criticisms (this point will be discussed), and its acceptance leads naturally to the scenario of a progressive enrichment by heavy elements of the matter in the galaxies. I will use here the concepts and the wording of these classical theories. I also have to stress that, owing to the enormous amount of literature about the subject, I will be unable in this limited space, to quote all the authors who have made significant contributions to the field, and I apologize for this uncompleteness.

In the standard Big Bang nucleosynthesis (BBN), the light elements D, ^{3}He,^{4}He, Li are formed in the first minutes of the expansion of the Universe, and the abundances reached at this time are linked with the ratio of photons to baryons, and therefore to the baryonic density of the Universe. Later on, these elements (except probably D) are also formed by various processes in stars, supernovae, cosmic rays etc. Some elements are fragile. The problem of the light elements is then to derive the primordial abundances from the observed abundances in more or less old objects currently observable, where the initial abundance has been more or less altered by subsequent production and/or depletion.

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2. Pop III stars

A solution would be the analysis of the so-called Population III stars, i. e. the old stars formed from the primordial matter. However, in spite of considerable efforts, these "first stars" have not yet been found (Beers et al. 1998, Cayrel 1996), and several hypotheses have been advanced for this scarcity : for example SN triggered star formation (e. g. Cayrel, 1986, Tsujimoto et al. 1999, etc.).

3. Methodology

We have therefore to collect the abundances in more or less young objects, and use the theories of the chemical evolution of the galaxies (essentially the evolution of our Galaxy) in order to restore the abundances in the old Pop III stars. The evolution theories are in reasonable agreement (far from perfect) with the observations (Chiappini et al. 1997).

4. Deuterium

D is observed :

-in the (young) interstellar gas, with a good uniformity in the local interstellar cloud (Linsky, this symposium) ; however some scatter is noted by Jenkins et al. (1999), see also Mullan & Linsky (1999), Sahu, Vidal-Madjar (this symposium) : the problem needs some clarification.

-in the solar system, the observations (solar wind, planets, meteorites) provide a coherent value within error bars

-in intergalactic gas, a few authors find, on one hand, high values (Songaila et al. 1994, Carswell et al. 1994), on the other hand Burles & Tytler (1998) find consistently rather low values. Molaro et al. (1999) find an object with a surprisingly low one (but see Levshakov, this symposium).

A better understanding of the exact nature, history and evolution of the intergalactic gas would be essential.

Some global information may be extracted from the currently available data, and a general trend extracted (Tosi 1998, Lemoine et al. 1999). Some uncertainty remains : is the scatter real (see Vidal-Madjar, this symposium) ? what is the source of the scatter ? is D only destroyed as generally assumed ? or significantly produced in stellar flares (Mullan & Linsky 1999) ? The data, to be obtained by FUSE, will help.

5. ^{3}He

In the young interstellar gas, the obtained abundance is about 2.5 10^{-5}. The H II regions provide a plateau (Balser et al. 1999), in contradiction with the standard model, which predicts some production in low-mass stars. Refined models (e. g. Charbonnel et al. 1998, Charbonnel & Do Nascimento 1998) explain the contradiction, as well as the high abundances found in some Planetary Nebulae.

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Formally, the plateau (the best configuration for a safe extrapolation), as well as the model of Tosi, provide a reliable value of the primordial abundance, but a better understanding of the evolution of ^{3}He in the Galaxy is desirable.

6. ^{4}He

Notation : the abundance is computed :

-by number of atoms : $y = N(He)/N(H)$

-by mass : Y, with $X + Y + Z = 1$ and $Y \sim 4y/\ (1 + 4y)$.

The primordial values are y_p and Y_p. Helium is essentially produced by the Big Bang. Later, all stars produce He, the bulk of the production is by massive stars. A general Galactic trend (progressive enrichment in He) is obvious, with however a large scatter and large error bars.

In the galaxies :

Blue compact galaxies (BCG) provide a better defined trend. Izotov & Thuan (1999) derive a high primordial He abundance, higher than in previous determinations : to be discussed.

The Y_p value depends rather heavily on the observations of the most metal-poor galaxies, such as I Zw 18. The history and structure of such objects are not yet fully understood.

7. Lithium

7.1. The ^{7}Li isotope

This isotope is produced in the Big Bang, with additional subsequent production

-by the Cosmic Rays

-possibly by the ν-process (Woosley et al. 1990) in SN II (controversial)

-by novae (controversial)

-by moderate-mass stars (AGB, Red Giants) on a long time scale

-in possibly significant amount by compact objects, cataclysmic variables, flares etc.

Notations : $A(Li) = \log(\varepsilon)\ Li = \log(\ N(Li)/N(H)\ ) + 12.00$

The observations show a trend in the Galaxy :

1) Young objects :

The field stars and clusters provide A(Li) = 3.0 - 3.3 dex, whereas the interstellar gas suggests a slightly larger value (3.5 dex).

2) Solar system :

A(Li) = 3.31 (meteoritic), but only 1.16 (photospheric), indicating a depletion of Li in the Sun, by a processus (or several ones) extending the convection. But the problem is not well understood : see for example the puzzling lack of correlation beween Li and age in the solar-type stars of the solar neighborhood (Spite and Spite 1982, Pasquini et al. 1994).

3) Old stars :

The Li abundance is uniform in Pop II dwarfs and subgiants

- for "warm" stars : $T_{eff} > 5700$ K
- for stars of low metallicity : $[Fe/H] < -1.4$ dex

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defining a two-dimensional plateau versus temperature and/or metallicity. Let us recall the notation [X] = log X_* − log $X_\odot$. The slopes of A(Li) versus T_{eff} and versus [Fe/H] are small or negligible. The abundance is around A(Li) = 2.2 dex (Bonifacio & Molaro 1997) when the temperature is in the IRFM scale (Alonso et al. 1996).

Finally, there is a definite trend of Li abundance in the Galaxy, but any interpretation has to take into account that Li is a fragile element. A number of contributions to this symposium discuss (section 9) the behavior of Li in stars in relation with various parameters (e. g. rotation, internal structure etc.).

4) Other galaxies :

In the Magellanic Clouds, the less processed interstellar matter has a low value of Li abundance : an argument in favor of a low primordial abundance. In the supergiants of the field, the behavior is similar to that found in the Galactic Pop I (Hill 1997).

DISCUSSION OF THE PLATEAU

Two interpretations have been proposed :

1 - A depletion of a high (primordial therefore uniform) abundance.

2 - A negligible depletion of a low (primordial therefore uniform) abundance.

In both cases, the *two slopes* of the plateau and the amplitude of the real *scatter* of the Li abundance around the plateau are both crucial AND controversial.

In the first interpretation, it is proposed that the same model of depletion, which works rather well for the Pop I stars, should apply to Pop II stars. The stellar structure is however clearly different in these two populations, in particular the depth of the convective zone (Cayrel 1998).

A detailed, documented and argumented review of the problem, by Cayrel (1999) from the observational point of view (and on the theoretical aspects by Vangioni-Flam et al. 1999), has been presented in the LiBeB workshop (Ramaty et al., ed. 1999).

A remark : The modest progressive enrichment of Li by cosmic rays (moderated by a modest depletion by stellar processing of Li in the massive stars) changes slightly the slope (Li versus [Fe/H]) of the plateau. The other slope of the plateau (Li versus T_{eff}) needs a good determination of the effective temperature : a fundamental problem (not yet solved) of stellar atmospheres.

Recently, Ryan et al. (1999) discussed a well delimited sub-sample of high quality observations, and in this way they obtained an observed scatter of Li abundances comparable to the errors, suggesting that the(intrinsic scatter is *very* small. The high accuracy, needed for reaching cosmological conclusions, is pushing the theory of stellar model atmospheres to its current limit.

We need

-best temperature determinations : interferometry, accurate multi-color photometry, accurate computed colors and threfore better stellar models

-2D or 3D convective atmosphere NLTE analysis (Asplund et al. 1999) : a considerable task (Cayrel and Asplund, this meeting).

Let us note that the model of Pinsonneault (1998) adjusted to the small observed scatter of the plateau, requires a limited depletion of lithium in Pop II dwarfs, implying a rather low Big Bang abundance, and consequently a large production of Li in the Galaxy.

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How is made this large production ?

- Novae : controversial
- Carbon stars, AGB (a significant source) and probably red giants.

A small proportion of red giants are found Li-rich, but this is important, since the red giants are very numerous and also since such an enrichment may remain local, perhaps explaining an inhomogeneous Li abundance in the Galaxy (e. g. the famous star BD 23 3912).

Our Brazilian colleagues have made a lot of work and observations about the Li-rich giants, as testified by their numerous contributions in this symposium (and see e. g. de la Reza et al. 1998, da Silva et al. 1995, Castilho et al. 1996). An important theoretical work has been done (Sackmann & Boothroyd 1999). The observations of Castilho et al. (1999) have shown that Li is not preserved, but produced in such giants. The discovery of a Li-rich giant in the cluster B 21 (Hill & Pasquini 1999) provides for the first time, in a moderately metal-poor open cluster, the chemical composition and the age of the star and its precise evolutionary phase.

7.2. ^{6}Li and the isotopic ratio

This isotope is produced in the Big Bang at a very low level. It is produced :

- in Cosmic Rays : see for example the LiBeB workshop (Ramaty et al., ed., 1999)
- in situ (not likely : Lambert, 1995)
- in flares (controversial)

The observed abundances :

Pop II and disk :

^{6}Li is measured only in two (three ?) Pop II stars (e. g. Smith et al. 1998, Cayrel et al. 1999) and two disk stars (Nissen et al. 1999).

Solar system : from meteorites, the ^{7}Li/^{6}Li isotopic ratio is around 12.

Interstellar matter : The isotopic ratio (and the abundance of ^{6}Li) is variable. The ratio : ^{7}Li/^{6}Li is around 1.1 towards ρ Oph, 6.8 and 5.5 towards ζ Oph and ζ Per respectively, and the revised value for ζ Oph (2 clouds) is a combination of two individual ratios : 8.6 et 2 (Lemoine et al. 1995). This variation suggests some local inhomogeneous production, the high value of the ratio in some clouds suggests a local production of the ^{7}Li isotope.

The ^{6}Li isotope is much more fragile than ^{7}Li, the presence of ^{6}Li in Pop II dwarfs, is an argument for a small (perhaps negligible ?) depletion of ^{7}Li on the plateau (controversial !).

8. Beryllium and Boron

Those elements are not supposed to be produced by the Big Bang, and do not provide any *direct* information about it (see however Suzuki, Yoshii & Kajino 1999). But their similarities with the other light elements (produced simultaneously with the Li isotopes, depleted in stars but less than D and Li) make that they are quite important in the general study of primordial abundances. These elements are not produced in stars, however B could be produced in SN II by the ν-process (Woosley et al. 1990). They are produced by the Cosmic Rays (see e. g. the LiBeB workshop, Ramaty et al., eds. 1999).

Recent observations in old "warm" metal-poor stars (Molaro et al. 1997, Duncan et al. 1997, Boesgaard et al. 1999, for Be, Duncan et al. (1998), Primas et al. (1999) for B), show that the abundances of Be and B vary in locksteps with the iron abundance, and the slope versus [Fe/H] is about one, suggesting a primary origin. However, the slope versus [O/H] is between 1 and 2 (García López et al. 1999), suggesting a mixed mode production, in agreement with the new models of Cosmic Rays.

The slopes (versus either Fe or O) are similar for Be and B, and the ratio B/Be remains constant (around 20).

There is a marked scatter, which suggests local inhomogeneities in the production of Be and B by the Cosmic Rays.

Interstellar matter : The abundance of B is there smaller than the meteoritic one (grain condensation). More interestingly, the ratio $^{11}B/^{10}B$ is 3.4 $\pm$ 0.7, in 3 clouds : it is similar to solar (4.05), different from the spallation ratio (2.5) suggesting a non classical production by the Cosmic Rays and/or by the ν-process (Woosley et al. 1990) .

B and Be are fragile. The meteoritic abundance of Be is 1.42 dex, the photospheric abundance is 1.15 dex, classically interpreted by a depletion of the fragile Be in the Sun, but Balachandran & Bell (1998) suggest rather an underestimation of the photospheric Be due to a bad estimation of the photospheric opacity in the UV : controversial.

The meteoritic abundance of B is 2.88 $\pm$ 0.04, the photospheric one is 2.6 $\pm$ 0.3dex

B is less fragile than Be : small (or no) depletion is expected in Pop II "warm" dwarfs (controversial ?), but some dilution of both Be and B is expected (and observed) in cool subgiants and giants.

9. Light elements as probes of stellar structure

As seen all along the previous sections, the fragile elements are probes of the stellar structure. This second aim of the observation of the light elements is essential for stellar studies, and by helping to gain a better knowledge of stellar structure (including convection), enables to gain a better accuracy and reliability of stellar abundances : an accuracy needed for reaching cosmological conclusions. However, the large variety of the sub-topics makes that it is extremely difficult to summarize briefly the numerous important and/or controversial points. Most of them are covered in the talks and posters of this symposium, in particular the complex relations between stellar rotation and lithium depletion.

10. Conclusion

The numerous problems and controversial points indicated here are discussed in this meeting. The accuracy needed for the abundances of the light elements, in order to reach cosmological conclusions, is at the limit of the possibilities of our current knowledge of stellar atmospheres and stellar structure. And the observed behavior of the fragile elements contribute to this knowledge. The interpretation of the abundances in gas is also difficult. The interaction of these different points of views is of course complex, and the aim of this symposium is to favor and develop fruitful exchanges. The excellent organisation of this colloquium, in an enchanting place, is definitely favoring discussions (both formal and informal), and also collaborations and progresses in this particularly exciting field : we all are grateful to the Local Organizing Committee.

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