Conclusions

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A view of the Amphithéatre Poincaré at the Ministère de la Recherche.

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From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Concluding remarks

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Abstract. Attempts are made to summarize some main points and results discussed at the IAU Symposium No. 228 in Paris, May 2005. It is concluded that, although the situation in areas pioneered by F. and M. Spite is nowdays rather complex, some important progress has recently been made, and more is expected to occur within the next few years if the level of ambition in the astronomical community is kept at the high level set by the pioneers.

Keywords. Stars: nuclear reactions, nucleosynthesis, abundances, stars: atmospheres, cosmology: observations

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1. Introduction: An obvious question and a messy situation

When arriving here a few days ago, many of us were impressed with the elaborated logotype of the meeting: this medal with Monique and Francois on its face. Several of us also asked ourselves the natural question what might be on the back of the medal. We considered the possibility that the medal would be introduced as a physical object at the banquet, e.g. presented to a promising young stellar spectroscopist, which would then give us a chance to satisfy our curiosity about the back by direct inspection. However, this did not happen. Why not? Could it be that no great prize-worthy progress has recently been made? True enough, Francois and Monique Spite have contributed a number of important achievements, as was described by Roger Cayrel in the opening session of this meeting such as the study of Ba and Eu in Pop II stars (1978), the grand discovery of the Li plateau (1982), the exploration of the chemical composition of stars in the Magellanic Clouds (1988-91), the discovery of the remarkably low scatter in relative abundances for Extreme Pop II stars (2004–05), and the recent measurement of Pb and U abundances in such stars. But, if you look at the scientific development, e.g. as presented at this meeting, after these beautiful and clear-cut first discoveries, it is tempting to agree with Roberto Gallino's sigh in the discussion the other day: "Rien n'est simple!". We should also remember that the symposium has been held in Amphithéatre Henri Poincaré, named after one of the early pioneers in the study of chaos. The choice of this room is proper. So, maybe the organizers did not find any good reason to present the medal, in view of the complexity of the situation. This situation may certainly be natural in a field of important development, but anyhow, it makes the task to summarize the meeting very difficult. I shall only, just like Poincaré mapped chaotic orbits by plotting their intersection points on a plane through phase space, make my map of the meeting by presenting its intersection with my personal interests and bias.

I shall not ask for excuse for this bias, but just say that in one particular respect I regret my selection of topics – I will only occasionally discuss the posters. This is a pity, since many of the posters at this meeting were truly interesting, and I urge all to study them carefully in the present publication.

2. The "romantic lithium" – and yet another plateau?

The beauty of the discovery of the Li plateau could be a reason to regard the element "romantic" (a characterization ascribed to Virginia Trimble by Susumu Inoue). Maybe its baffling abundance – being close to constant with a small scatter and only a possible small dependence on effective temperature and metallicity for Pop II stars in the relevant temperature interval, but with an offset of 0.3–0.5 dex from the logarithmic value 2.6 implied by WMAP, makes it even more romantic, or at least enigmatic (see Sean Ryan's and Piercarlo Bonifacio's presentations). Geoffrey Burbidge reminded us that this situation, with the observed abundances of ^{2}D, ^{4}He and ^{7}Li being mutually significantly inconsistent with the predictions from Big Bang nucleosynthesis, is not satisfactory, while Ann Boesgaard claimed that consistency could be obtained with WMAP predictions for Li, if depletion (à la Pinsonneault) and chemical-evolution effects are accounted for. Alain Coc argued that the cosmological value of the ^{7}Li abundance based on the WMAP baryon density estimate could hardly be affected by uncertain nuclear cross sections by more than 0.1 dex. Sean Ryan did not expect that 3D effects and non-LTE effects could affect the abundance analysis by the amount required to explain the difference, and instead advocated stellar depletion, e.g. due to turbulent diffusion. It then has to be a very regular phenomenon, affecting most stars on the plateau similarly. Also the effects of systematic errors in the effective temperature scale were pointed out by Ryan and Meléndez *et al.* (poster).

A number of departures of stars from the plateau were also noted. E.g., certain stars in globular clusters depart, possibly due to rotation. Anna Frebel showed that her new record holder in iron abundance, HE 1327-2326 with [Fe/H]$= -5.4$, does not show any Li although it seems to have parameters like the plateau stars. On the other hand, Francois Spite pointed at the fact that metal-poor stars that are rich in nitrogen, indicating processed material, still may appear on the plateau.

As disturbing, and interesting, as the departures from the WMAP value for the ^{7}Li plateau are the results reported by Martin Asplund and collaborators on the ^{6}Li abundance of the Pop II stars. The suggested tendency for the ^{6}Li values to line up at a constant logarithmic abundance of about 1.0 dex on the scale where the abundance of ^{7}Li is about 2.1 dex is remarkable: yet another plateau! No doubt, this spectroscopic exercise is very difficult, and there are several stars with only upper limits. Also, the fact that some of the most metal-rich stars in the sample of stars with ^{6}Li determinations have this "plateau" value in spite of the fact that galactic spallation models predict higher ^{6}Li abundances is intriguing. In this situation, it is natural to urge us to scrutinize our basic methods and understanding of the atomic physics and the line-formation theory involved in modelling stellar spectra – there are after all as yet few examples of testing our current theories with line profiles at such high signal-to-noise ratios in halo stars. However, if no errors in the modelling are found, far-reaching conclusions may be necessary. If the new plateau survives further tests and further data, the hypothesis that it is primordial, or even cosmological, seems tempting, and will lead towards further studies of, e.g. the formation of ^{6}Li by reactions due to decay of exotic particles (e.g. Jedamzik (2004)), or by structure-formation shocks (cf. the presentation by Susumu Inoue), or cosmological cosmic rays (Emmanuel Rollinde). A burning question is then how the depletion of ^{7}Li from its cosmological value by more than a factor of two could occur, without the destruction of all ^{6}Li in the stars.

3. The very first stars

While "for many years we did not discuss them" (quote from Francesca Matteucci) the first stars (Pop III stars, Bond (1981)) are now at focus. This is much due to the systematic work made by several groups in surveying the properties of the most metal-poor stars, the finding of some extremely metal-poor stars in these surveys, and polarization results of the WMAP satellite suggesting a dating of the re-ionization of the early universe to a few hundred million years after the Big Bang and the conclusion that this re-ionization was probably produced by stars. Frédéric Daigne showed at the meeting how the models for the re-ionization are considerably constrained by the observed properties of the very metal-poor stars.

Volker Bromm argued in his presentation that the formation of the first stars was easier to model than the birth of later stellar generations, since the primeval gas was free of dust and perhaps magnetic fields. These stars are thought to have masses around $10^2\,M_{\odot}$, high effective temperatures and are smaller than Pop I stars by a factor of 4 at a given mass, due to the low opacity. Rotational mixing has strong effects on their wind yields, warned André Maeder. So has also a very small pollution by metals, as was explained by Georges Meynet (see also poster by Raphael Hirschi), who compared the effects of metals with the effects of perfume – "so much emotion for such a small mass!" Considerable amounts of nitrogen are produced, but further N production is needed along the halo phase in Francesca Matteucci's models. Dave Arnett brought in another important factor in any yield calculations, and not the least those for supernovae and AGB stars – the effects of internal waves which have to be modeled realistically by abandoning 1D models. The low-order modes lead to asymmetries and abundance inhomogeneities, as Arnett demonstrated in beautiful movies showing numerical 2D and 3D simulations. It seems that rotation and waves must be included consistently in future realistic 3D models of these objects.

Tim Beers and Norbert Christlieb discussed the different surveys for metal-poor stars, the HK survey, the HES, the DR3 and the ongoing SEGUE, as well as the coming SSHS and LAMOST surveys. Beers presented a metallicity distribution for Pop II and mentioned the interesting possibility that there is a significant lack of stars in the interval $-5 \leqslant [Fe/H] \leqslant -4$. Nikos Prantzos wondered whether this smooth distribution complies with our ideas about hierarchical structure formation. Judith Cohen and Thomas Masseron commented on the distribution of [C/Fe] – of great significance for the understanding of the reason for the considerable fraction of carbon-rich metal-poor stars. In the metal-poor end there may be a natural selection effect since carbon-poor gas may have difficulties to cool enough to admit star formation. For the high percentage of metal-poor carbon-rich red giants, there may also be simple explanations: "The problem is to *avoid* C-stars in Population II", as Roberto Gallino phrased it.

The new surveys are no doubt very significant steps towards a better understanding of the evolution of the Galaxy. When later Gaia results are available, the situation will be qualitatively different. However, let us just remind ourselves of the fact that knowing and controlling the bias in the surveys is as important as the hunt for ever more sensational objects, as expressed in the ancient verse:

If you wish to become a master
I have a basic secret to tell:
You don't have to work any faster
but ought to know bias and errors well.

An important development in using these increasing stellar samples for systematic studies of chemical evolution was demonstrated by Paul Barklem, who has designed automatic methods for model-atmosphere synthetic-spectrum analyses of low S/N spectra. He has applied these methods to hundreds of HES stars suspected to be rich in neutron-capture (n) elements, with promising and reliable results.

Anna Frebel presented her record star HE1327-2326, and pointed out its virtues: since it is a turn-off star or a subgiant it is improbable that its comparatively high C, N and Mg abundances are due to self-enrichment. Iwamoto *et al.* (2005) have recently suggested that the heavy elements of this star and of the most metal-poor giant HE0107-5240 were made in fall-back core-collapse SNe. This was discussed by Ken'ichi Nomoto at the meeting who demonstrated that moderate variations of the free parameters of their model, the explosion energy (or the mass-cut), as well as parameters for overshooting and diffusion, to fit the Na, Al and N abundances, could reproduce the abundance patterns of both stars. Although applied to spherically symmetric models these parameters, he speculated, might mimic the effects of rotation or bipolar flows. A suspected second uranium star was also introduced by Norbert Christlieb and Vanessa Hill, CS29497-004, with an estimated logarithmic uranium abundance of 1.7–2.0 dex, implying reasonable U/Th ages. On the assumption that the detection of the UII line at 385.95 nm would be confirmed, it was dubbed by Christlieb to "Hill's star".

4. The abundance-scatter problem and calculated yields

Monique Spite showed in her presentation the small scatter in relative abundances of Mg/Fe, Na/Fe and Al/Fe ($<$0.1 dex, see also Arnone *et al.* (2005)) for dwarfs in the First-Stars Project. The problem how this phenomenon could be understood, considering the fact that the relative yields of different elements are highly dependent on initial SN mass according to current models of SN II, is severe and seems to require efficient mixing processes and/or a relatively slow formation of the second generation of stars in the early Galaxy. As noted by Nikos Prantzos the idea about hierarchical structure formation may be challenged by these findings. Torgny Karlsson argued that the small scatter may possibly be due to cosmic selection effects – that only SNe in a limited mass interval would lead to enrichments small enough to produce the most metal-poor stars. He also introduced a new acronym, SSSs, Single-Supernova Sequences, which could be observable in the relative-abundance diagrams (where abundance ratios are plotted for different heavy elements) as narrow sequences, representing stars made of material only affected by one SN. This, however, requires accuracies of better than 0.05 in relative abundances. Jason Prochaska also pointed out that the abundance scatter relative to Si seems small in damped Lyα systems.

Unlike e.g the alpha elements the more heavy elements, like Ba and Eu, show a significant real scatter relative to Fe around [Fe/H] ~ -3 according to Gabriele Cescutti. Assuming that this is due to small number statistics, such that the number of sources N(n) contributing n-rich elements is small relative to the total number of SNII, N(II), one may estimate from the observed scatter in [s/Fe] relative to that in [α/Fe] that N(n) $< 0.01\,$N(II) (see also the poster by Yuhri Ishimaru *et al.*).

Stéphane Goriely discussed the yields of s-elements and concluded that they are very well represented by theoretical calculations for solar abundances, but that the production of these elements in Pop II stars is still not well understood. V453 Oph, which is rich in s-elements but still C-poor, is an interesting problematic example. Jim Truran reviewed the still uncertain sites for the r-elements, whether neutron-star collisions or neutrino winds in massive stars or something else, and pointed out that a special distinct process,

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not necessarily at different sites, is needed to explain the abundances of elements with A < 140. Other enigmas discussed in this connection were the Eu and N abundances of CEMP stars (Sara Lucatello) and the departing abundance pattern for the n-element poor of prototype Pop II giant HD 122563 (introduced by Satoshi Honda). Inese Ivans introduced the first Bi abundance derivded for a metal-poor star (the lead-rich CS29497-30) but found the observed Bi/Pb ratio to agree with predictions for the s-process.

The yield calculations for the massive pair-creation-instability supernovae were reviewed by Alexander Heger who concluded that they are not (yet) needed. Marco Limongi noted problems with fitting Ti, Sc, Cr, Co and Zn abundances from zero-metallicity core-collapse SNe for any unique choice of mass-cut – a problem that might be reduced for non-spherical models, according to Nikos Prantzos. Carla Fröhlich has explored convection and neutrino interaction in SN models further, and showed much improved results for Sc and Zn yields. Corinne Charbonnel discussed yield calculations for red giants and noted, when comparing with globular cluster observations, severe problems with the expected increase of C+N+O due to hot-bottom burning, with reproducing the observed O vs Na anticorrelation and the Mg isotopic ratios. She concluded by stating that “there is no satisfactory predictive power of AGB models right now” and suspected the unsatisfactory treatment of convection and/or rotational mixing to be the reason.

A general comment on the yields and their use in the study of the chemical evolution of galaxies is the following: Very much evidence in this field is indirect and built on parametrized descriptions of star-formation, initial mass functions, mixing in the ISM, stellar evolution, internal mixing in stars, stellar mass loss, yes even in abundance analysis. This is a dangerous situation, as was known long ago:

If you allow me to carry some parameters along
I can prove that your measurements agree
with my favourite theory although it is wrong
as also your data may be.

In order to base this study on a sound physical basis it is very important to restrict the extensive array of sometimes rather unphysical parameters. Therefore, physically self-consistent yield calculations are very significant, as are “direct” observations of yields in SNe, PNe and AGB stars. In the latter difficult fields much more systematic efforts are well motivated (Gustafsson (2004)). At the meeting very few presentations were devoted to such efforts, among them Grazyna Stasinska’s report about a planetary nebula with a metallicity as low as 1/100 solar.

5. Globular clusters, bulges, dwarf galaxies and high-z systems

The study of different stellar populations, with e.g. different star-formation rates, are interesting from a galaxy-evolution point of view, but also since the relative abundances give clues on the characteristic build-up times of different elements and thus empirical information concerning their nucleosynthesis sites.

Somebody made the comment at another meeting that “I always loose my concentration when the globular-cluster talks start, with all those special things for affinados of NGCs”. This time, however, that comment was improper. A number of significant results were shown and questions were asked. Chris Sneden pointed out that although primordial and evolutionary effects are mixed in the globular clusters as expressed in light-element abundances, cluster stars and field stars in general show striking similarities for heavy elements that indicate a common nucleosynthesis history. An example was given by Jennifer Sobeck, presenting results for Mn. Raffaele Gratton demonstrated with beautiful VLT-Flames spectra that the *blue* side of the ωCen main sequence is the metal-rich one, suggesting that these stars are He-rich ($Y \sim 0.40$) which caused intensive comments. Gary Da Costa had CNO, Sr and Ba results, again for stars on the ωCen main sequence, and found less correlations between abundance variations than expected. Luca Pasquini has studied Li in M 92 and NGC 6397 and found a plateau-like behaviour, also for stars with Mg, Al and Na anomalies which is astonishing since that gas should have been processed earlier and burnt Li. Stars in the more metal-rich NGC 6397 show a clear Li-Na anticorrelation. Verne Smith showed that flourine correlates with O in M 4 giants which gives further constraints on the origin of the chemical inhomogeneities.

For the galactic bulge, with an overall metallicity close to the solar one, some alpha element enhancement relative to iron is found (Livia Origlia, see also poster by Alves-Bito & Barbuy) which then indicates a more rapid star formation rate than in the galactic disk and might suggest a connection to the halo. Pascale Jablonka, however, showed indications that the bulge of M31 is similar in [Fe/H] in spite of the metal-rich halo of that galaxy which, when comparing with the results for the Milky Way system, seems to support the view that the origins of the halo and the bulge are not strongly linked.

The impressive development in the study of Local Group dwarf galaxies is continuing, as was shown by several studies presented at the meeting. Nobuo Arimoto demonstrated that Leo A, in spite of its smallness, has a disk and a faint halo, and may be the result of hiearchical formation. It seems to also suffer from a G-dwarf problem. Kim Venn noted that the Sculptor dwarf indeed has metal-poor stars with compositions reminding of the Galactic halo stars, while the more metal-rich stars in the dwarf galaxy have smaller alpha enhancements relative to iron. Luciana Pompeia had obtained reduced alpha/Fe ratios in the inner disk of LMC (indicating slower star formation rate there than in the Galaxy), as well as high abundances of heavy s elements as compared with corresponding galactic stars, and lower abundances of the light s elements which agrees well with the notion that the heavy ones are produced in lower-mass AGB stars.

At least as impressive were the results for the high-redshift systems. Claus Leitherer discussed integrated spectroscopy for Lyman-break galaxies in the redshift interval $2.0 \leqslant z \leqslant 3.5$ as based on hydrodynamical model atmospheres of O and B stars with winds (Rix, Pettini, Leitherer, *et al.* (2004)) with a convincing agreement between observed and calculated spectra. Typical metal abundances were about 0.4 times solar, with possible evidence for enhanced alpha elements. Joop Schaye discussed the intergalactic medium between $1.5 \leqslant z \leqslant 6$ and found low carbon abundances and very great abundance inhomogeneities, though little systematic variation with redshift. Jason Prochaska and several others discussed the Damped Lyman Alpha systems, commonly interpreted as galaxies in early evolutionary phases. In spite of problems with ionization, and some saturation, the relative abundances resulting for the gas are claimed to be accurate to 0.01–0.02 dex, which would then be among the most accurate abundance determinations available in astrophysics! The severe dust depletion, however, is a problem. Although some decrease with metallicity with increasing redshift may be traced, there is a heavy real scatter at a given redshift. The lowest metallcity found is -2.6; the metallicity distribution for the systems in fact is similar to the distribution for Galactic globular-clusters.

Finally, an interesting result was given by Yeshe Fenner. If the results by Murphy, Webb & Flambaum (2003), indicating time variability in the value of the fine-structure "constant", are to be explained by variations in the isotopic ratios of Mg as a function of time, it seems hard to explain this in terms of enhanced numbers of intermediate-mass stars producing ^{25,26}Mg , since that would overproduce N in the DLAs.

6. Some final comments

6.1. *"Do we really deserve high-resolution high S/N spectra?"*

The quote in the subtitle above was given by Chris Sneden, who cited Pierre Magain's comment at the Paris symposium in 1987 on the impact of the new generation of stellar spectrometers. Now, the spectrometers have reached an even higher degree of sophistication and are also attached to bigger telescopes. They deliver excellent data, at considerable costs. But is the standard of the analysis on a corresponding level?

In fact, errors in current abundance analyses also for very faint stars are totally dominated by errors in model atmospheres, calculated spectra and errors in background physics, or *lack* of physics. True enough, also uncertainties in fundamental parameters, such as effective temperature, play a role here, but those are then often related to the uncertainties in the models and their spectra. Typical errors in abundances for metal-poor stars due to non-LTE and 3D may well amount to 0.5 dex or even more (cf. the posters by Collet *et al.*, Fabbian *et al.* and Korn & Mashonkina) and may vary systematically with [Fe/H]. Thus, reported trends with metallicity may be affected, or even qualitatively changed by systematic errors. For at least 40 years such alarming messages have been brought forward by theorists, and usually been left unconsidered by observers, since there has not been much to do about them. Now, it gets possible to do something, at costs considerable smaller than those for developing present telescopes and spectrometers. One striking and effective demonstration of both the effects as such and the existing possibilities of handling them is the current work by Asplund and collaborators on the solar CNO abundances (cf. Asplund *et al.* (2005) and references cited therein), which shows corrections to established values of more than 0.2 dex!

Thus, spectral analysis of stars with convection zones close to the atmospheres should be made by 3D models, in deriving absolute abundances or differential abundances for stellar samples with some range in fundamental parameters. Non-LTE effects should be considered seriously in these analyses. They will still often be uncertain, due to uncertainties in cross sections for atomic and molecular collisions with hydrogen atoms and electrons. Systematic efforts to improve that situation, by quantum-mechanical calculations, careful calibration on certain stars with very well-known parameters and very detailed spectroscopic data, and possibly by laboratory measurements, should be made.

How do we accomplish this in practice? Key factors are not lack of ideas or physical insight or numerical algorithms, sooner organizational matters. Most theorists in astrophysics have other, maybe more fundamental questions in mind, e.g. those related to dark energy or planetary-system formation. To compete with these areas in attracting good modellers, one must offer good positions and fruitful scientific collaboration. These people should be fully integrated into the projects and might well be observers also; in general one should regard their modelling as part of the calibration of the observations, sooner than some theoretical magics. The new methods should also be tought in considerable detail to all observers. This does not exclude the possibility, yes necessity, that theoretical astrophysicists also make fundamental studies of, say, the formation of magnetic structures in stellar atmospheres, or the interaction between plasma waves, radiation and dust. But, in the calibration of high-quality observational abundance data, one should set aside resources for adequate analysis, just as for the equipment. Anything but that seems unprofessional.

Somebody at this meeting said: "0.3 dex? Who cares?" Personally, I believe that we shall, and already have, discovered important new things when the systematic errors are reduced. Good examples are the fine structures discovered by several groups for stars in the halo-thick disk-thin disk transitions, see, e.g., the posters of Bensby & Feltzing and

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Decauwer *et al.* A realistic goal is to get the systematic absolute abundance errors below 0.10 dex, and the relative errors below 0.03 dex, when similar stars are compared.

6.2. *A sociological observation*

A simple sociological development became very obvious at this meeting. People are forming large research collaborations and consortia, they are "teaming up". There were teams announced, such as the "First-stars team", the "HES industry" and, if I did not mis-hear, "Team Beers". There was "The Texas-Lick Axis", DART, etc. Astrophysics is gradually approaching a state where particle physics was some 40 years ago. The basic reason for this may be the growth of instrumentation costs, but probably the enormous growth of the data volumes that may be obtained is at least as important. Anyhow, in transcending from a small-group science to an medium-group science we should learn from the experience made by particle and space physicists. The sociology of large-scale international projects has been studied systematically, and it seems important that we consider the results of that study in organizing our further collaborations.

6.3. *"Are you Francois Spite?"*

Sean Ryan told us that when he participated as a young scientist in the Elba meeting, he asked a French scientist the question above, and got the answer: "No ... I wish I was". This brings us to the delicate question, whether Francois and Monique now think that we are living up to their standards. I am not sure about that, and guided by this uncertainty I suggest that the back of the medal symbolizing this meeting should have the inscription:

Pour un cadeau
de deux pionniers
tel le plateau.
Qu'il faut bosser!

which may be paraphrased *To receive such gifts/from the Spites/and match their vision/requires ambition.* This may seem demanding, difficult to match. However, in this world of high ideals, there is also mercy, as was very nicely expressed by Francois in the end of his talk: *... my wife and I are very proud to belong to a community where friendship finally overcomes any (temporary) divergence of opinion.* I trust that all of us are happy to be included into this community, and thankful to the initiators and organizers of this conference for bringing us here on this memorable occasion.

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