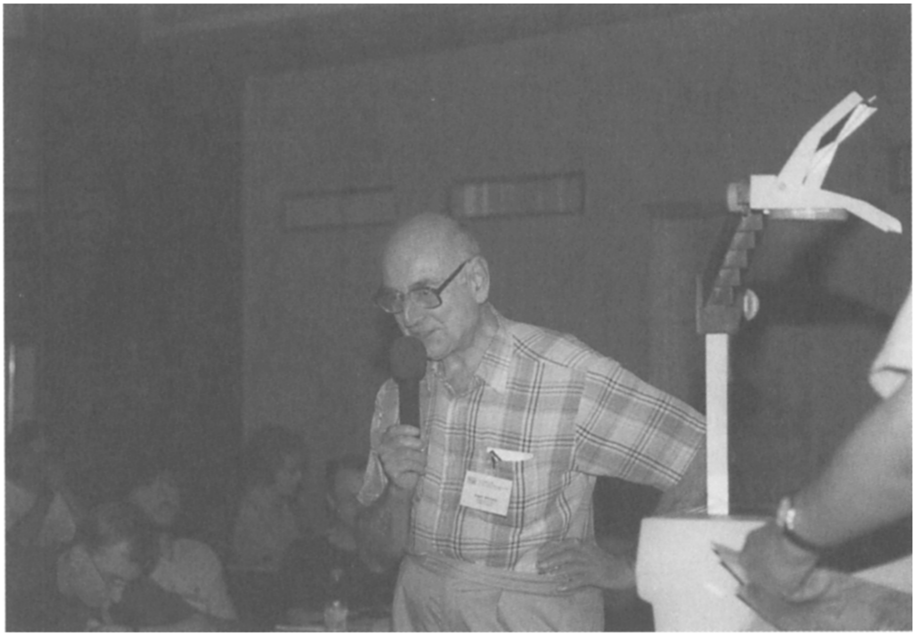
CONCLUSIONS



Bernard Pagel presenting his Conclusions

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Conclusions I

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Abstract. Some conclusions are drawn from the Conference as to Big Bang Nucleosynthesis, cosmic rays, AGB star evolution and various kinds of mixing processes in stars.

1. Introduction

The last symposium on Light Elements that I remember was held on Elba in 1994 (Crane 1995). Thinking of that meeting reminds me of how much we have lost through the untimely death of Dave Schramm, whose breadth and enthusiasm would have added so much to this meeting had he been spared.

The problems we face are to find the abundances of light elements (D, ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B) as functions of place and time and thereby find out about Big Bang nucleosynthesis (BBNS), Galactic cosmic rays and production and destruction by stars in the course of Galactic chemical evolution (GCE). In this quest we face a number of difficulties, notably abundance uncertainties due to errors in parameters, inhomogeneities and departures from LTE in stellar atmospheres, collisional effects, fluorescence and underlying absorption in H II regions affecting ^{4}He, and unexplained scatter, notably for D.

2. Elements relevant to BBNS

2.1. Deuterium and ^{3}He

Starting with deuterium, there is now a handful of convincing measurements at high red-shifts in Lyman-limit systems where there is no reason to doubt that the abundance is primordial. Garry Steigman gave comparable weight to the 'high D' ($D/H > 10^{-4}$, say) and 'low D' values, but in my view all the 'high D' estimates in the literature suffer from such technical flaws that we can dismiss them. The convincing work is that by Dave Tytler and his students using the Keck telescopes.

How low is 'low'? Here Sergei Levshakov has made an important contribution by introducing the idea of mesoturbulence, related to the still more sophisticated analysis of local clouds presented by Jeff Linsky. The upshot is that primordial D/H is between 3 and about 5×10^{-5}, corresponding to η_{10} between 4 and 6.

This range of η is also in agreement with measurements of ^{3}He (which seems to be pretty much neutral to GCE effects) in Galactic H II regions reported by Tom Bania and Bob Rood.

Coming to more local objects – the Solar System and the interstellar medium (ISM) – one expects a downward trend with time in the sense $D_{\mathrm{hi}\,z} > D_{\mathrm{SS}} > D_{\mathrm{local\ ISM}}$ and a positive gradient with galactocentric distance. Some evidence for the latter was provided by the Galactic centre observations reported by Don Lubowich, which can be compared to published observations of the D I hyperfine structure line towards the anticentre by Chengalur, Braun & Burton (1997).

In the Solar System, George Gloeckler gave $D/H = 1.9 \times 10^{-5}$ at high heliocentric latitudes measured from the *Ulysses* satellite, while in the local ISM after allowing for emission-line profiles, hydrogen walls and other factors, Jeff Linsky gives 1.6×10^{-5}, all of which seems quite reasonable. Models of GCE allow the corresponding astration factor between 2 and 3, as reported by Monica Tosi and Cristina Chiappini, although this concordance may be taken as supporting those models as much as supporting the primordial D/H value.

All this is very nice, but there could be a fly in the ointment: Is D/H constant? Alfred Vidal-Madjar made an eloquent case for variations, but Meena Sahu has argued that, for stars within 100 pc or so, this case does not really hold up. Further afield, there are the obstinate cases of γ^2 Vel and δ Ori that have been around since the time of *Copernicus* and, as noted by George Sonneborn, these have not been explained away so far. Perhaps Sergei Levshakov could get to work on these cases. In any case, there will be more data from the *Fuse* mission in the near future.

2.2. ^{4}He

Pagel et al. (1992) derived a primordial helium abundance $Y_{\mathrm{P}} = 0.228$, which is certainly too low; as transpired afterwards, we underestimated effects of underlying absorption lines in I Zw 18 and there could be other factors. Izotov & Thuan have presented the results of a splendid job based on a uniform set of observations with high signal:noise deriving $Y_{\mathrm{P}} = 0.244$ and a plausible value of dY/dZ, consistent with results reported by Walter Maciel for planetary nebulae and with stellar data (Pagel & Portinari 1998). The error bars quoted by Izotov & Thuan are overly optimistic; we estimated a systematic error of up to 0.005, and even that may be optimistic.

There are various effects, e.g. ionization correction factors (as discussed by Sueli Viegas), collisional excitation of hydrogen and maybe some real inhomogeneity. Thus it would be useful to have observations with a higher spectral resolution, as Thuan plans to do, helping to check up on underlying absorption (as Keith Olive pointed out) and measuring lines from higher energy levels that are less sensitive to collisional excitation.

Manuel Peimbert, who – with Silvia – started this whole business back in 1974, presented some exremely nice work on NGC 346 in the SMC avoiding some of the problems, notably that of underlying absorption. They find a lower helium abundance $Y_{\mathrm{ngc\,346}} = 0.241 \pm 0.002$ extrapolating to $Y_{\mathrm{P}} = 0.236$.

What are we to make of this? I think it best not to rely on one single object, however good, as there must be intrinsic scatter at some level. We should therefore hold our horses before deciding that there is a discrepancy with 'low' deuterium and standard BBNS with $N_\nu = 3$.

2.3. ^{7}Li

On ^{7}Li we have had no less than 25 papers and 18 posters. It is not possible to summarise all of them, and I apologise for ignoring many significant contributions. The classical Spite plateau, according to Sean Ryan's very careful discussion, survives previous attempts to superimpose a cosmic scatter, but on the other hand now seems to have a slight slope due to cosmic-ray production, as is to be expected from the presence of ^{6}Li that Poul Nissen reported on. The CR contribution to ^{7}Li at $[\mathrm{Fe/H}] = -2$ is at least 5 per cent, possibly more.

Possible destruction factors in the atmospheres of Population II dwarfs and subgiants now seem to be very severely limited by the small scatter and presence of ^{6}Li (0.15 dex according to Marc Pinsonneault and 0.1 dex according to Sylvie Vauclair), although the relevant factors are not completely understood. Concerning the abundance determinations themselves, we have a reassurance at least in the particular case of the subgiant HD 140283 from Martin Asplund who showed that effects of atmospheric inhomogeneity are more or less cancelled out by non-LTE effects, and from a similar study described by Roger Cayrel. Is this like using Satan to cast out Beelzebub? In any case this is very impressive fundamental work dispensing with the usual fudge factors associated with model atmospheres.

Taka Kajino described new nuclear physics results that reassure us that the theoretical uncertainties in primordial abundances have not been underestimated. Thus with Ryan's estimate $1.96 \leq 12 + \log(\mathrm{Li/H})_\mathrm{P} \leq 2.38$ and the upper range of 'low' deuterium we have concordance in the range

$$4 \leq \eta_{10} \leq 5; \quad 0.014 \leq \Omega_\mathrm{B} h^2 \leq 0.019, \tag{1}$$

in good agreement with what has been deduced on other grounds from the Lyman-α forest. The corresponding range of Y_P is between 0.242 and 0.247, and we heard from Hannu Kurki-Suonio that the simple homogeneous Big Bang is still the best model.

3. Lithium and Galactic chemical evolution

It has been clear for a long time that ^{7}Li in Population I needs stellar sources as well as Galactic cosmic rays (GCR) since, as Hubert Reeves has mentioned, the solar-system ratio $^7\mathrm{Li}/^6\mathrm{Li} = 12$ is so high.

Fig 1 shows some GCE models invoking AGB stars, supernovae etc. by Matteucci et al. (1995) together with a very simple-minded model that just assumes $^7\mathrm{Li}-{}^7\mathrm{Li}_\mathrm{P} \propto \mathrm{Fe}$ normalized to the Solar System. These models seem to have some quite desirable properties in relation to Sean Ryan's conclusions in that the Li abundance begins to rise noticeably at $[\mathrm{Fe/H}] = -2.5$ and very noticeably between -2 and -1, whereas the more recent models shown in Fig 2 are a bit too flat in this region. On the other hand, there seems to be a steeper rise above $[\mathrm{Fe/H}] = -1$, which suggests the influence of a class of stars having a still longer evolutionary lifetime than the SNIa reponsible for the bulk of the iron, and two of the models by Romano (1999) shown in Fig 2 do this by appealing to novae, but I think AGB stars of sufficiently low mass would do equally well, and this is relevant to several papers that we heard at this meeting.

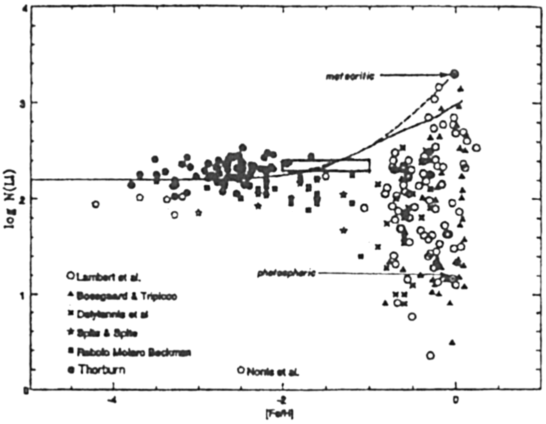

Figure 1. Stellar lithium abundances as a function of metallicity. The full-drawn curve shows the prediction of the GCE model by Matteucci, D'Antona & Timmes (1995), assuming contributions from carbon stars, massive AGB stars and SNII, while the broken-line curve gives the sum of a primordial component and an additional component proportional to iron and normalized to meteoritic abundance. The rectangle shows the range of undepleted lithium abundances at metallicities $-2 < [Fe/H] < -1$ reported by Ryan at this conference. Adapted from Pagel (1997).

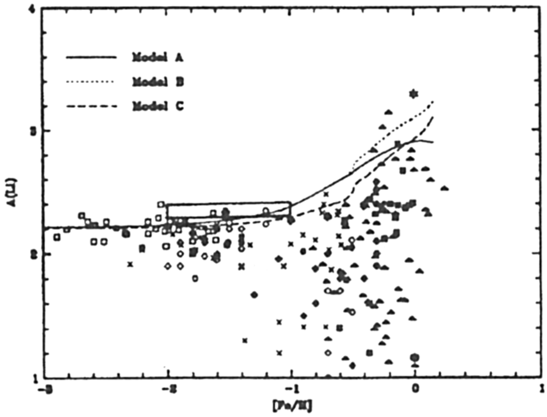

Figure 2. Stellar lithium abundances as a function of metallicity. The curves represent numerical models by Romano (1999): A with ^{7}Li production from carbon stars, massive AGB stars and SNII; B the same with addition of thermonuclear runaway in nova outbursts; C like B but without any contribution from carbon stars and a lower one from massive AGB stars and SNII. The rectangle shows the range of undepleted lithium abundances at metallicities $-2 < [Fe/H] < -1$ reported by Ryan at this conference. Adapted from Romano (1999).

I may mention in particular the stimulating and eloquent presentation by Juliana Sackmann. There are basically two modes of ^{7}Li production by the Cameron–Fowler mechanism: hot-bottom burning in massive stars on the AGB; and cool-bottom burning in low-mass and preferably low-metallicity stars on the RGB. Things basically happen at the red-giant clump where the H-burning shell encounters H, ^{3}He rich material from the previous maximum penetration of the surface convection zone, μ-barriers are reduced and fresh ^{3}He becomes available to make ^{7}Be. This kind of source was also discussed by Corinne Charbonnel, as both a sink and a source of ^{7}Li (the example of a sink in the cooler component of Capella was discussed by George Wallerstein (1966) many years ago).

At this meeting, a wealth of observational evidence was presented, notably the PDS survey here in Brazil described by Ramiro de la Reza, Carlos Torres and Bruno Castilho. It seems that, at a critical stage, your K giant can emit a dust cloud detectable by IRAS, which expands, cools and disappears, so the star does a loop in the HR diagram possibly supplying fresh ^{7}Li to the interstellar medium in the process. However, as Gerard Jasniewicz pointed out, other mechanisms such as engulfing planets etc. are not ruled out.

Yet other aspects of lithium depletion/non-depletion have been discussed. Rafael Rebolo showed some beautiful results on brown dwarfs, where lithium supplies a useful diagnostic and alternative age estimator for clusters and he even suggests that Population II brown dwarfs could potentially supply an alternative estimate for primordial lithium. In any case, Yakiv Pavlenko now achieves impressive results with synthetic spectra.

There is considerable new data on lithium depletion in Galactic clusters. The theory, described by Constantine Deliyannis, envisages some sort of slow mixing generated by rotation accompanied by diffusion, and Georges Michaud gave a very detailed diffusion model for Am and Fm stars. Coming back to lithium, one may single out Vanessa Hill's study of NGC 2473 and 47 Tuc, two clusters of similar metallicity but different ages and with turnoffs on either side of the Boesgaard lithium gap. The depletions are similar in the two cases, supporting Luca Pasquini's conclusion that most of the depletion on the main sequence occurs in a relatively short time like 10^8 years.

Finally, we have the lithium isotope anomalies in the ISM, described by Dave Knauth who confirms previous suspicions of ratios as low as 2 towards o Per, which suggests a large contribution from cosmic rays. Is there any relation with the suspected D/H anomalies? Conversely, we heard from Francesca Primas about the halo star HD 160617 which has plateau-like lithium but anomalously low beryllium and boron, suggesting an unusually low exposure to cosmic rays. This star also has high nitrogen, but it is not clear whether that has any connection.

4. Elements produced by Galactic cosmic rays

Cosmic rays (GCR) are thought to be the main source of ^{6}Li, Be and B, although ^{11}B can also have a contribution from the neutrino process in supernovae. In the classical model of Reeves, Fowler & Hoyle (1970), the main process is the hitting of stationary interstellar CNO nuclei by relativistic protons and α-particles in the GCR, with a minor contribution from the inverse process, and this more-or-less accounts for the abundances of these species in the Solar System apart from underpredicting the $^{11}B/^{10}B$ ratio. The latter might have been explained by postulating a low-energy GCR component, but the whole idea is challenged by the 'primary' behaviour of Be and B relative to iron at low metallicities.

If the O/Fe ratio steadily rises towards low metallicity as claimed by Israelian, Garcia-Lopez & Rebolo (1998) and by Boesgaard et al. (1999), then the trend relative to oxygen has a slope of about 1.5, intermediate between primary and secondary. Fields & Olive have managed to fit a basically secondary GCR model to this trend, but we heard from Etienne Parizot and Reuven Ramaty that the energetic difficulties associated with the secondary model still remain.

This problem bears on the origin of cosmic rays as well as on the enrichment of stars and the ISM in the early Galaxy. Etienne Parizot, Michel Cassé and Reuven Ramaty have discussed various forms of primary models which in general involve formation of stars in a superbubble wherein ejecta from one or more supernovae mix with the ambient ISM leading to energetic particles with CNO nuclei present, but models differ in the precise details of the mechanism and location of GCR acceleration.

I do not go into details on that, but just note that, in these situations, metallicity (however defined) is not a good clock, but rather a measure of the environment — how massive the supernova was and how far away from the low-mass stars that we observe now — so the 1.5 power of O-abundance (if indeed that is what it is, of which I am not yet convinced; cf. Fulbright & Kraft 1999) can be a measure of the relative abilities of the two elements to escape from the SN environment, and one expects a certain amount of scatter as indeed has been found for the r-process (Tsujimoto, Shigeyama & Yoshii 1999). Also, oxygen can vary relative to metals like magnesium, as a result of gas-dust separation.

Other related issues are the roles of a low-energy component and of the ν-process. ^{6}Li is very considerably enhanced relative to Be in low-metallicity stars compared to the Solar System (the exact amount depending on what view is taken of its depletion) and it seems that $\alpha - \alpha$ fusion is not enough to account for this, so a low-energy component may still be needed. Whether B/Be varies at all with metallicity is still an open question, and — as Francesca Primas informed us — isotopic data for boron are awaited.

Beryllium and boron, while more robust than lithium, nevertheless are destroyed at temperatures of 5 million K or so and therefore together with lithium provide important constraints on the depth of mixing, e.g. in the Sun, where we heard from Suchitra Balachandran that beryllium is quite undepleted, implying that mixing is confined to a relatively narrow layer below the outer convection zone. Another issue raised by this work is the UV opacity affecting OH lines, which were used by Balachandran & Bell to calibrate the opacity using theoretical f-values, whereas Israelian and Boesgaard et al. changed the f-values to fit solar data with Kurucz models. However, the changes are small, typically 0.1 dex or so, and so do not have a major bearing on the conflict between these authors and Fulbright & Kraft on the O/Fe ratio. I think Israelian had a good point on nLTE effects in gravity determination from ionization equilibrium; on the other hand I would not either trust HIPPARCOS parallaxes when they are so small. So in my opinion that issue remains open.

Boron is another element affected by UV opacity and there was an impressive treatment by Katia Cunha, both for the Sun, where again the photosphere is brought into agreement with meteorites, and for hot stars where nLTE effects are being brought under control. Again, boron seems to track iron, but not oxygen, in the Orion association — another little piece of data probably telling us something, but I don't know what.

So we have plenty of data, a little more understanding maybe, plenty of controversies and plenty to be done. It just remains to thank the organizers and our Brazilian hosts for the opportunity to enjoy this very lively meeting in such a splendid environment.

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