Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press)

Conference Summary

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Abstract

Highlights of the meeting include new insights into *r*- and *s*-processes and an explosion of interesting abundance data on stars in the Galactic halo and in dwarf spheroidal galaxies. I include in this summary a few suggestions on the chemical evolution of the thick and thin disks, and on the present and past distribution of baryons and metals in the Universe.

1.1 Introduction

It has been a great pleasure and honor for me to be able to attend this fascinating Symposium, and I should like to express my warm thanks to Andy McWilliam and Michael Rauch for inviting me. Clearly the Carnegie Observatories (or Mount Wilson as I still like to think of them) are carrying their illustrious traditions forward into their second century of existence.

1.2 History

George Preston recalled some highlights associated with the names of G. E. Hale, A. S. King, H. N. Russell, Horace Babcock, Lawrence Aller, Paul Merrill et al. I was intrigued to hear that after the discovery of stellar technetium Merrill began to pay much more attention to unconventional new ideas; I think he would have enjoyed this conference!

Margaret Burbidge described the steps leading up to current ideas on nucleosynthesis, beginning with Hoyle's pioneering work in 1946, through the peaks in the standard abundance distribution, and her work with Geoff on the barium star HD 46407, to B^2FH and subsequent developments. I remember visiting Margaret and Geoff in their small apartment in Botolph Lane, Cambridge, all covered in tracings, in 1954.

1.3 The Overall Picture

George Wallerstein raised some of the questions that form a backdrop to much of our proceedings, notably the issue of galaxy formation by monolithic collapse versus a series of mergers, and the extent to which the Galactic halo could have been formed from dwarf spheroidals. Abundance characteristics like the α/Fe ratio preclude such a possibility for the classical globular clusters, but some field stars, especially with retrograde orbits, might originate in captured dwarfs.

1.4 Nucleosynthetic Yields

1.4.1 Massive Stars

Yields from massive stars were discussed by Dave Arnett, Claudia Travaglio, and Ken Nomoto. There are basically two kinds of process: hydrostatic burning (hydrogen, helium, carbon and neon burning, and *s*-process) and explosive synthesis (oxygen and silicon burning and the *r* and *rp*-processes). Laser plasma experiments have led to improved knowledge of opacities and equations of state, but the structure of supernova remnants (SNRs) like Cas A shows up the limitations of one-dimensional models; 2-D and 3-D models are under development and help to "educate" the 1-D models (e.g., by discovering instabilities), but the explosion mechanism is still uncertain.

The abundance peculiarities of extremely metal-deficient stars (notably Christlieb's star HE 0107–5240 with [Fe/H] = −5.3), include excesses (relative to iron) of C, N, O, α-elements, Zn, and Co, and deficiencies of Cr and Mn. Ken Nomoto was able to explain these abundance patterns from nucleosynthesis by Pop III supernovae (SNe) with masses anywhere between 20 and 130 $M_\odot$ forming massive black holes with mixing–fallback in the ejecta, combined with the SN-induced star formation model in which, for a given yield, Fe/H is inversely proportional to the explosion energy. Strong mixing and fall-back explains the cases with strongly enhanced C and O and corresponds to an observed class of faint SNe (IIp), while higher explosion energies (possibly assisted by rotation) produce hypernovae (some of classes Ic and IIn), in which complete Si burning leads to α-element excess and the peculiarities in the iron group.

The *r*-process, reviewed by John Cowan, still holds many mysteries, since its path involves highly unstable nuclei, and there is no certainty as to where it occurs; Grant Mathews favors the neutrino-heated hot SN bubble, but neutron star pairs are another candidate and, in any case, magnetic fields, jets, and neutrino oscillations may be involved. Some intriguing nuclear information has come from H-bomb tests (Stephen Becker).

Among the lowest-metallicity stars, there are huge variations in the relative abundance of *r*-process and iron-group elements, while among the *r*-process nuclides themselves there is sometimes excellent agreement with the solar system *r*-process distribution and sometimes not, especially between the $A \simeq 130$ Xe peak and the higher Pt peak. So, as previously suggested by Wasserburg, Busso, & Gallino (1996) on other grounds, there may be two or more distinct *r*-processes, analogous to the weak and main *s*-processes. This, in turn, relates to radioactive cosmochronology, to which we return later.

1.4.2 Low- and Intermediate-mass Stars

Intermediate-mass stars are significant sources of He, C, N, and the main *s*-process elements. We heard from Dick Henry that, compared with the old work of Renzini and Voli, widely used despite their own health warnings for so many years, more recent synthetic models like those of van den Hoek & Groenevegen predict higher mass loss rates, less helium production, and an increase in C and N production at lower metallicities. Hot-bottom burning sets in at around $3\,M_\odot$, and C and N production is further enhanced by rotation. There is fair agreement with abundances found in planetary nebulae. A somewhat contentious issue is raised by the bimodal distribution of N/α ratios in damped Lyα systems, the upper branch corresponding to N/O in H II galaxies and the lower branch nearly an order of magnitude lower; could this be an age effect, or is there something funny going on with the initial mass function? Mercedes Mollá described galactic chemical evolution models with a new set of yields for carbon and nitrogen, and Amanda Karakas discussed the production of aluminum (including ^{26}Al) and heavy magnesium isotopes in AGB stars.

Rotation also influences mixing processes following the first dredge-up (Corinne Charbonnel). At the bump in the luminosity function where the H-burning shell crosses the previous lowest boundary of the outer convection zone, the μ-barrier is partially lifted, enabling various extra-mixing processes to take place as a result of rotation. Consequences include lowering of the ^{12}C/^{13}C ratio, destruction of ^{3}He and the production of a lithium "flash" leading to enhanced mass loss attested by a dust shell after a brief super-lithium rich phase.

Significant, perhaps even dominant, contributions to Galactic enrichment in ^{7}Li, ^{13}C, ^{15}N, and ^{26}Al come from novae (Sumner Starrfield); UV spectra of some fast novae show enhanced abundances of N, O, Ne, Mg, and Al, but not C or Si.

Dramatic advances in the theory of the *s*-process have resulted from the efforts of the Torino group, presented by Maurizio Busso and Oscar Straniero. Evidence from branchings in the Kr–Rb region confirms that most of the main *s*-process with neutrons from ^{13}C takes place during shell H-burning phases between thermal pulses, with just a minor top-up from ^{22}Ne during the pulses themselves. This renders obsolete the old idea of an exponential distribution of exposures (Seeger, Fowler, & Clayton 1965), which I described in my book as arguably the most elegant result in the whole of nucleosynthesis theory! The steps at magic numbers are still there, however. A free parameter in the theory is the mass of the ^{13}C pocket that gets ingested into the intershell zone. This seems to be more or less constant, leading to increasing neutron exposures with lowering metallicity, and eventually to a "strong" *s*-process with lots of lead (confirmed by Judy Cohen).

1.5 Modeling Galactic Chemical Evolution

According to taste, there is a great variety in the degree of sophistication and complexity that one can put into galactic chemical evolution models, ranging from chemodynamical and cosmological SPH plus semi-analytic simulations (as described by Brad Gibson), to numerical models with parameterized star formation and gas flow laws (Francesca Matteucci), to highly simplified analytical toy models, which still have a useful contribution to make, as was shown at this meeting by Verne Smith and Matt Shetrone, for example. The wide range in *r*-process/Fe ratios in the most metal-poor stars suggests some kind of inhomogeneous model (Sally Oey), although the simplest version of this postulates a threshold that is not observed and predicts far too many metal-free stars.

1.6 Stellar Abundance Analysis

Substantial revisions in the "official" solar oxygen abundance in the last two years led to some doubts as to how good stellar abundances really are and the influence of bandwagon effects. Bengt Gustafsson described the activities of "sheep" (who follow the crowd) and "goats" (who like to put a spanner in the works, but not too big a one). I believe the comparison with emission lines from H II regions is a good check (see Table 1.1). To one place of decimals in the log (to quote two would be like a second marriage—a triumph of hope over experience!), the agreement is gratifyingly good, or rather was, until Kim Venn dropped her WLM bombshell at this meeting! The H II O abundance is typical for such a dwarf galaxy, whereas the stellar one is surprisingly high. We heard from Andreas Korn and

Table 1.1. *CNO Abundances in Local Group Galaxies*

Object	C	N	O	Reference
Local Galaxy:				
Sun	8.4	(7.8?)	8.7	Allende Prieto et al. 2001, 2002
Sun	8.6	7.9	8.7	Holweger 2001
Orion nebula	8.5	7.8	8.7	Esteban et al. 1998
diffuse ISM			8.6 to 8.7	Meyer, Jura, & Cardelli 1998
cepheids	8.0/8.6		8.3/8.9	Luck et al. 1998
M 31:				
H II regions		7.0/8.2	8.5/9.2	Dennefeld & Kunth 1981
SNR		7.4/8.0	8.3/8.7	Blair, Kirshner, & Chevalier 1982
4 AF supergiants	8.3		8.8	Venn et al. 2000
M 33:				
H II regions		7.9–.16*R*	9.0–.12*R*	Vílchez et al. 1988
SNR		7.8–.12*R*	8.8–.07*R*	Blair & Kirshner 1985
B,A supergiants			9.0–.16*R*	Monteverde et al. 1997
LMC:				
H II regions, SNR	7.9	6.9	8.4	Garnett 1999
cepheids	7.7/8.3		8.0/8.8	Luck et al. 1998
PS 34-16 (early B)	7.1	7.5	8.4	Rolleston et al. 1996
LH 104-24 (early B)	7.5	7.7	8.5	Rolleston et al. 1996
NGC 1818/D1	7.8	7.4	8.5	Korn et al. 2002
NGC2004 (4 early B)	8.1	7.0	8.4	Korn et al. 2002
4 F supergiants	8.1			Russell & Bessell 1989
SMC:				
H II regions, SNR	7.5	6.6	8.1	Kurt et al. 1999
cepheids	7.4/7.8		8.0/8.3	Luck et al. 1998
10 A supergiants	$< 7.3/< 8.7$	6.8/7.7	8.1	Venn 1999
3 F supergiants	7.7		8.1	Spite, Barbuy, & Spite 1989
2 F supergiants	7.8			Russell & Bessell 1989
NGC 6822:				
H II regions		6.6	8.3	Pagel, Edmunds, & Smith 1980
H II regions			8.4	Pilyugin 2001
2 A supergiants			8.4	Venn et al. 2001
WLM:				
H II regions		6.5	7.8	Skillman, Terlevich, & Melnick 1989
A supergiants		7.5	8.4	Venn 2004

Norbert Przybilla how important it still is to get better atomic data for both LTE and non-LTE abundance analyses, and from Mariagrazia Franchini about the possibilities of using the Lick indices to get α/Fe ratios.

1.7 Abundance Effects from Internal Stellar Evolution

Dave Lambert discussed the wide range of effects observed in AGB and post-AGB stars. Hot-bottom burning may break through into the Ne-Na and Mg-Al cycles, leading to peculiarities in ^{26}Mg/^{24}Mg ratios in NGC 6752 and some field dwarfs. Hot-bottom burning can also lead to ^{7}Li and fluorine production, and a final shell-flash seems to be responsible for the effects found in FG Sge and H-poor carbon stars like Sakurai's object and R Cr B. RV Tau stars, a class of post-AGB stars, are apparently metal-poor because refractories are locked on dust, resulting in an enhancement of *s*-process/Fe ratios, which in turn correlate with heavy/light *s*-process ratios (Maarten Reyniers). There is now direct evidence for *s*-process enhancements in planetary nebulae (Harriet Dinerstein).

Light elements are affected by mixing processes even in the main sequence stage. Anne Boesgaard has discovered a beryllium dip in open clusters like the Hyades, which shows interesting contrasts to the lithium dip. Within the dip, Be is down, though not as much as Li, which is reminiscent of effects of rotational mixing on ^{6}Li/^{7}Li (Pinsonneault et al. 1999), whereas on the cool side Be is undepleted for quite a long way, which corresponds more to a vertically stratified model with a deeper exclusion zone for Be than for Li.

1.8 Abundances in Stellar Populations

1.8.1 The Milky Way Halo

The study of the oldest stars in our Galaxy, some of which appear to have lower metallicity than anything seen at high redshifts up to now, was justly described by John Norris as "near-field cosmology." The records are held by G77–61 ([Fe/H] $\simeq$ –5.5) and Christlieb's star ([Fe/H] $\simeq$ –5.3), discovered in the Hamburg Objective Prism survey, but the numbers fall below expectations from the Simple Model for the halo below [Fe/H] = –4 (Norbert Christlieb searched 5 million stars to get 2000 extremely metal-poor candidates), a result explained by Tsujimoto, Shigeyama, & Yoshii (2000) in terms of SN-induced star formation. Further candidates are likely to be found from the huge database provided by the Sloan Digital Sky Survey with the aid of automated spectrum analysis (Carlos Allende Prieto). Lithium abundances on the Spite plateau are a bit uncomfortably low for Big Bang nucleosynthesis in the light of deuterium and cosmic microwave background fluctuation spectrum data, so there has to be quite a bit of depletion, by a factor of 3 or so, and the presence or absence of a metallicity dependence hinges on subtleties in the abundance analysis. Some globular cluster stars show higher lithium abundances and a scatter (Boesgaard).

Below [Fe/H] = –3, very large relative overabundances of the CNO elements are sometimes found (see Nomoto's and Judy Cohen's talks), and in a few cases this also applies to Mg, Si, and Eu, but for most stars α/Fe is quite flat down to [Fe/H] = –4, while Co/Fe rises and Mn, Cr/Fe fall with decreasing metallicity. Among neutron-capture elements, Sr varies wildly, in contrast to Ba, and the ratio of *r*-process to iron is highly variable.

New data from UVES on the ESO VLT exhibit a remarkably uniform and flat trend in α/Fe ratios between [Fe/H] = –2 and –4 (Monique Spite). I remarked that only analytical toy models could account for such a flat trend, but Francesca disagreed. According to Monique's data, oxygen shows only a modest overabundance down to [Fe/H] = –3.5, apart from the odd exception; this hot issue, also discussed by Suchitra Balachandran and in a poster by Garik Israelian, was delicately tiptoed around by speakers and audience.

With the discovery of uranium in CS 31082–001, radioactive cosmochronology has at last become respectable (Roger Cayrel). For a long time, the Th/Eu ratio has been used for this purpose, following a suggestion of mine (Pagel 1989), and at first I was a bit miffed at this not having been mentioned, but now that this ratio has been exposed as a quite unreliable one (see also Otsuki, Mathews, & Kajino 2002), I suppose I really should be grateful!

1.8.2 The Thin and Thick Disks

Thick-disk stars (essentially the same as Bengt Strömgren's "Intermediate Population II") resemble bulge stars with minor differences, i.e. they continue to display the α-rich effect noted by George Wallerstein 40 years ago (Wallerstein 1962), up to quite high metallicities, symptomatic of an old get-rich-quick stellar population, while in the halo both α-rich and non-α-rich stars are found, the latter belonging to the outer halo and showing similarities in composition to dwarf spheroidals and irregulars (Poul Nissen). In the thick disk, however, as appears from recent work reported by Sophia Feltzing (as well as the Edvardsson et al. 1993 survey and other studies), the α/Fe ratio does actually come down at high metallicities, indicating a significant contribution from SNe Ia as well as possible effects of a star formation threshold (Cristina Chiappini). While the time needed for a significant contribution from SNe Ia is often assumed to be of the order of 1 Gyr, in reality there must be a spread, so that it is still hard to be quantitative about the age and formation time scale of the thick disk, but a sketch of how the chemical evolution of both disks might have gone is shown in Figure 1.1. A new version of the Edvardsson et al. (1993) survey is under way (Bacham Reddy).

1.8.3 The Galactic Bulge

Our host Andy McWilliam has been making heroic efforts over the years, in collaboration with Mike Rich, to gain accurate abundances for red giants in the bulge. Their latest results on K giants show trends in α-elements that are rather like those in the thick disk, with O, Mg, and Si high (as well as Al and Eu), but O/Fe coming down at the highest metallicities. Ca/Fe behaves like in the thin disk, which is interesting because Lambert et al. (1996) found a similar effect in the RR Lyrae stars, presumably representing the thick disk. What is this telling us about the origin of calcium? Near-infrared spectra enable the abundance analysis to be extended to M giants in globular clusters (Livia Origlia).

1.8.4 Globular Clusters

The globular cluster metallicity scale has been refined by using Fe II (Bob Kraft). Galactic globular clusters all have [Fe/H] ≥ -2.4, but in many respects show similar abundance patterns to field stars in the same metallicity range (Chris Sneden). The main differences are the Na,Al–O anticorrelation (although Al abundances are still a bit dodgy) and the persistence of CNO anomalies down to the main sequence, suggesting a multi-generational aspect to globular clusters. Ruprecht 106 is exceptional and may be a captured system, and the inner-halo–outer halo effects found in field stars have a counterpart in globular clusters, e.g. M4 versus M5 (Jon Fulbright). Still stronger anomalies are found in a few cases (Inese Ivans).

The most intriguing globular cluster (or galaxy remnant?) is, of course, ω Centauri, with metallicities ranging from [Fe/H] $= -2$ to zero, and high s-process abundances (Verne Smith; Elena Pancino). Lanthanum, a heavy s-process product, shows a stepwise increase with Fe/H at [Fe/H] $= -1.6$, while the light s-process element yttrium varies less. ω Cen displays both cluster-like (Na–O anticorrelation) and dwarf galaxy-like properties (low α/Fe, Eu/Fe). The metal-poor component shows rotation, whereas the metal-rich one does not, all of which suggests a merger of two extragalactic globular clusters and capture into the Milky Way. A model by Takuji Tsujimoto envisages three star formation episodes, the first terminated by a wind whereafter AGB stars enriched the remaining gas with heavy s-process elements; in the

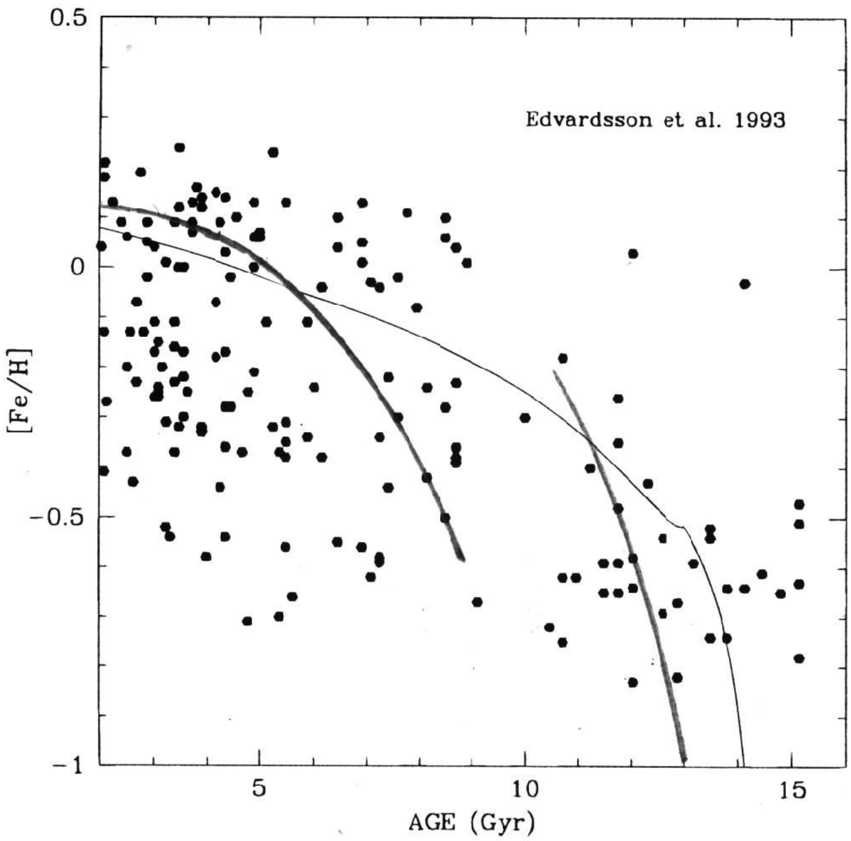

Fig. 1.1. Thin curves: age-metallicity relation from the “two-inflow” model of Chiappini, Matteucci, & Gratton (1997). Thick curves: sketch of suggested age-metallicity relations for the thick and thin disks. Data points from Edvardsson et al. (1993). Adapted from Chiappini et al. (1997); reproduced from Pagel (2001).

third phase SN Ia-induced star formation occurred, and the remaining gas was stripped by passage through the Milky Way disk. He ascribes the difference from other globular clusters to formation by colliding protocluster clouds; low-impact velocities favor SN-induced star formation and chemical evolution, whereas high velocities prevent it.

1.8.5 Nearby Galaxies

The LMC has stars of all ages, despite the gap in the cluster age distribution, and a fairly well-defined age-metallicity relation; it remains to be clarified how “bursty” the star formation history has been (Vanessa Hill). Carbon and nitrogen abundances are low, as in blue compact galaxies, suggesting youth, but α/Fe and O/Fe ratios are also low, suggesting a long star formation time scale. There are also substantial differences between clusters of similar age and metallicity in both Clouds (Jennifer Johnson).

Stellar wind analysis techniques (Fabio Bresolin) applied to A-supergiants in gas-rich dwarf galaxies NGC 6822, Sextans, and GR 8 give oxygen abundances in good agreement with H II regions in the same galaxies, and also metal abundances, which indicate [α/Fe] $\simeq 0$ down to [Fe/H] $\simeq -1.5$ (Kim Venn), but for WLM there is a discrepancy (see Table 1.1). The common finding of solar α/Fe is somewhat puzzling: is there something fundamental about it (e.g., as a consequence of star formation bursts), or does it imply largely common star formation histories? These differ considerably in detail, although age-metallicity relations are often similar within the uncertainties (Eva Grebel). In any case, there is not the large variety in α/Fe ratios suggested by Gilmore & Wyse (1991).

High-resolution spectroscopy with large telescopes has also led to detailed information about ages and compositions in dwarf spheroidal galaxies (Matt Shetrone). These divide into those with a simple star formation history dominated by an early burst (e.g., Dra, Sex, UMi, Scl) and those with a more complicated one (e.g., Sgr, For, Car, Leo I and II). The simple group provides new insights into nucleosynthesis: O,Mg/Fe start to go down when [Fe/H] ≥ -1.5, suggesting that star formation was interrupted, and Ca and Ti are less enhanced than O and Mg, due to explosive versus hydrostatic synthesis or a contribution from SNe Ia? The metallicity dependence of Mn and Cu is not due to the latter effect, as can be deduced also from their behavior in the Galactic halo. Y and Na are low, while Ba/Y is high, indicating *s*-process production in metal-poor AGB stars.

Complex star formation histories place constraints on hierarchical galaxy formation models (Tammy Smecker-Hane). Dwarf spheroidals mostly follow a metallicity-luminosity relation, $Z \propto L^{0.3}$, as do gas-rich dwarfs, though with a lower zero-point, but not for the reasons given by Dekel & Silk (1986), which require a simple history culminating in a terminal wind, and it seems that total luminosity is more important for metallicity than are the details of star formation history (Carmen Gallart). Furthermore, giant elliptical galaxies cannot have been made up from dwarf spheroidals. The main difference between gas-rich and gas-poor dwarf galaxies is that the latter have been robbed of their gas by the Milky Way and M 31, probably through ram pressure (Jay Gallagher).

The metallicity-luminosity relation extends all the way up to M 31, which has a disturbed, metal-rich halo with [Fe/H] $\simeq -0.6$ like 47 Tuc (Mike Rich) and many blue horizontal-branch stars indicating great age. The globular cluster system rotates and includes a globular cluster/captured dSph very like ω Cen.

1.9 The Interstellar Medium

X-ray satellites *ASCA* and *Chandra* now permit spatially resolved abundance determinations in SNRs (John Hughes). In SNe II these are lumpy and diverse, and the accuracy of relative abundances depends on the species compared being in the same place. Cas A has at least four components, of which one is a featureless nonthermal continuum while others represent O-burning (Si, S) and incomplete Si-burning (Fe). One can have "inside-out" configurations in which iron-group elements overtake the lighter ones. SN Ia remnants are smoother, but may contain lumps of hot iron!

Various solid pieces of stars are found as presolar grains in meteorites (Don Clayton) and provide constraints on the chemical evolution of the Galaxy. "Mainstream" SiC grains come from AGB stars (with relatively low ^{12}C/^{13}C and high ^{14}N/^{15}N), but there are also "X" grains from SNe where these ratios are reversed. The silicon isotopes present something of a mystery because the plot of ^{29}Si excess vs. ^{30}Si excess has a slope of 1.3 and passes above the (solar) origin, although the stellar sources must have been older and presumably less metal rich than the Sun. My suggestion is that there may be a bias toward high metallicity in the sample, e.g. if stellar winds are metallicity-dependent. Isotopic and elemental patterns in the grains suggest a well-mixed Galactic chemical evolution (Larry Nittler).

However, interstellar dust does not consist of unmodified solid ejecta from stars; these are subject to shocks, sputtering, etc. in the interstellar medium (ISM), and some return to the gas phase with a typical turnover time of 3×10^8 yr and there is grain growth in the ISM (Bruce Draine). Various clues suggest the composition and size distribution of the dust: 2200 Å absorption comes from sp^2-bonded carbon in sheets (graphite or PAH), diffuse interstellar bands from large molecules (?), 3.4 μm features from C–H stretches in linear chains and mid-infrared features from PAHs and Si–O stretches. The ratio of visual absorption to reddening increases with the size of the particles, which is mostly under 1μm.

UV spectra (from *Copernicus* to *FUSE*) reveal how much of the standard abundance distribution is depleted from the gas to the dust phase, but sometimes ionization corrections are needed (Ed Jenkins). The revised solar O and C abundances lead to a more consistent picture than one had before (cf. Table 1.1), and there is now some information about the composition of high-velocity clouds and the Magellanic Stream, which resembles that in dwarf irregular/blue compact galaxies. In the Galactic plane, the D/H ratio is uniform in the local bubble (100 pc), but shows anomalous variations further afield—only 7.5×10^{-6} on the sightlines to λ Sco and δ Ori, but 2.2×10^{-5} on that to γ^2 Vel (Jeff Linsky). Could deuterium be locked on grains? This would hardly account for the unusually large value, but a spatially and temporally varying infall of relatively unprocessed matter might. No deuterated molecules were detected in a cloud 28 kpc from the Galactic Center by Don Lubowich, but molecular features are rather weak there anyway.

Absorption lines of molecules such as CO, CN, HNC, and HCO^+ can now be studied by a new technique using interferometry (Tommy Wiklind). In both diffuse and dark clouds, CO and HCO^+ are much more abundant than expected from gas-phase reaction networks, while O_2 is expected but not seen. CO has been detected in emission from far-infrared-luminous galaxies/AGNs up to a redshift of 4.7. and many molecules have been found in absorption up to $z = 0.9$; relative abundances are similar to those found locally.

1.10 The Local Universe

Galactic winds resulting from SN activity in starburst galaxies can strongly influence chemical evolution, depending on the depth of the potential well and the structure of ambient gas (Crystal Martin). Hot SN ejecta are removed in the wind, but not much of the ISM. High-density winds appear in X-ray images (e.g., NGC 3077 and NGC 1569), whereas low-density winds are detected from blue-shifted absorption lines (e.g., in ultra-luminous infrared galaxies). Mass flow rates are comparable to star formation rates, but in big galaxies it is not clear that all the material involved escapes, nor is it clear whether large or small galaxies make the dominant contribution to the intergalactic medium.

Abundances in stellar populations can be studied on the basis of integrated light using the Lick indices (Scott Trager) calibrated on globular clusters. The age-metallicity degeneracy is broken using Hβ, provided there is no emission or extended blue horizontal branch, but one does need accurate and complete isochrones and a spectral library. Some results indicate nitrogen enhancements in red giants of M 31 and Fornax, but not in old clusters of the LMC, while conversely these have an α/Fe enhancement while Fornax does not. Ellipticals in the Coma cluster are older than field ellipticals, both with α enhancement, while S0s have a spread in age with less α enhancement, but the ages are less robust than the chemical results, which will be extended to less prominent elements in the near future. The calcium triplet in ellipticals is anomalously weak, either because of bad fitting functions or because of some anomaly in Ca/Mg (see Galactic bulge!).

Another approach to composition variations between and across galaxies comes from H II regions (Don Garnett). There are some problems, including temperature fluctuations and the calibration of R_{23} (which I sometimes think of like Macbeth as "Bloody instructions which, being taught, return to plague the inventor"!), but there is quite good agreement with young stars (Table 1.1). Oxygen abundance gradients in non-barred spirals such as M 101 are quite constant at –0.2 dex per scale length, a simple result that may need a complicated explanation. The metallicity-luminosity relation translates into an effective yield (abundance/*ln* gas fraction) that increases with rotational velocity (representing mass) up to a point and then levels off, presumably when SN-driven winds no longer escape. Iron abundances can sometimes be found from Fe II lines—prominent in AGNs and some peculiar stars like η Carinae— taking account of UV pumping from Lyα and other sources; for example, in Orion it is about 1/10 solar in the gas phase (Ekaterina Verner).

One of the benefits of the SDSS is the possibility to study the star formation rate density in the local Universe from a complete sample of Hα emission (Jarle Brinchmann). The major contribution comes from dusty, high-metallicity, high-surface brightness spirals and the star formation rate is about 1/4 of the past average, in agreement with the Madau plot and its various updatings (e.g., Steidel et al. 1999).

ASCA and *XMM-Newton* spectra of numerous clusters of galaxies have provided new details about the composition of the intracluster medium (Michael Loewenstein). There is no evolution with redshift up to $z = 0.8$, but some variation with temperature of the X-ray gas. CNO/Fe are as in the Galactic disk, with subsolar metallicity, but Si and Ni are relatively overabundant, and the composition cannot be represented by any combination of conventional SNe Ia and SNe II. Could there be a Population III contribution?

1.11 The High-redshift Universe

The composition of the broad emission-line gas in quasars bears witness to the effect of rapid star formation accompanying that of the central black hole (Fred Hamann). In other words, there exists a get-rich-quick population suitable for the black hole's future role as the core of a massive spheroidal system. Absolute abundances are model dependent, but the high relative abundance of N compared to C and especially O is suggestive of a high metallicity like twice solar, and the mass of the region is similar to that of a globular cluster. Intrinsic, narrow absorption lines confirm at least solar abundance of carbon.

Next in metallicity (and in ambient mass density) after quasars come the Lyman-break galaxies (Kurt Adelberger), about which much has been found out from the lensed object cB58. The abundance of oxygen is about 1/3 solar, while the interstellar lines indicate a lower abundance of iron-group elements in the gas phase. The P Cygni profile of C IV resembles that of stars in the LMC. Lyα has a violet-shifted component indicating outflows at 300–600 km s^{-1}, which perturb and enrich the intergalactic medium out to 0.5 Mpc, leading to a correlation between Lyman-break galaxies and intergalactic C IV. So we witness SN feedback in action.

Next in the scale come the damped Lyα systems which may be the raw material for disk galaxies today (Jason Prochaska, Paolo Molaro, Francesco Calura). Metallicity, measured by zinc, shows only a mild evolution with redshift from 2 to 6, and there are problems from

Table 1.2. *Baryon and Metal Budgets (after Finoguenov et al. 2003)*

		$z = 0$			
Component	$Z, 10^{-2}$	$\Omega_Z,\ 10^{-5}$		$\Omega_b,\ 10^{-2}$	
Stars	1.2[a]	2.3 – 4.6	— Most	0.2 – 0.4	
O VI absorbers	0.26	1.8 – 5.2	— metals	0.7 – 2.0	— Most
Lyα forest	0.01	0.1		1.2	— baryons
X-ray gas, clusters	0.7	1.4		0.2	
Total	0.28	5.6 – 11.3 [b]		2.3 – 3.8	
Predicted				3.9	
		$z = 2.5$			
Protocl. gas	0.7	1.4	— Most	0.2	
ISM, dust	0.8	0.8 – 1.7	— metals	0.1 – 0.2	
Lyα forest	0.01	0.1 – 0.3		1 – 5	— Most baryons
DLAs	0.1	0.1		0.1	
Total	0.1	2.4 – 3.5		1.4 – 5.5	
Predicted		1.6 – 3.2		3.9	

[a] i.e. solar.
[b] $\Rightarrow$ yield $\equiv \Omega_Z/\Omega_{\rm stars} \simeq 0.028$

dust: selection bias and differential depletion from the gas phase. As was already mentioned by Dick Henry, N/α is bimodal, the low branch being attributed by Jason to massive Pop III stars, but I prefer Paolo's explanation in terms of the yield from conventional massive stars, enhanced by rotation as described by Meynet & Maeder (2002). Sub-damped Lyα absorber systems, with N(HI) $\simeq 10^{19}$ cm^{-2}, contribute significantly to the gas and metal budgets and show stronger evolution with z (Céline Peroux).

Finally, we come to the intergalactic medium, aka the Lyα forest (Bob Carswell, Rob Simcoe), which is sparse at low redshift and best seen at $z = 2$ to 3. Usable lines are from C IV, N V, Si IV, and (buried in the Lyα forest) O VI. O VI/C IV gives electron densities agreeing with SPH simulations, and this, with ionizing flux estimated from Si IV/C IV, enables some abundance estimates to be made: [C/H] $\simeq -2$ in the neighborhood of galaxies. More sensitivity is obtained by stacking C IV spectra and computing pixel optical depths; some weird enriched regions have been found in this way. No chemically pristine regions have been found (Rob Simcoe). Typically [C/H] $\simeq -2.5$ whenever Lyα is seen, although it can go down as low as -3.5; the problem is that one is fighting against ever diminishing column densities!

1.12 Conclusions

Highlights of this conference have been in my view the new insights into the s- and r-processes and the explosive increase in details of stellar abundances in the Galactic halo and in dwarf spheroidals, together with their star formation history and age-metallicity relations.

B. E. J. Pagel

I do not think a conference on the origin and evolution of the elements would be complete without a survey of where the baryons and metals are in the Universe as a whole, and where they were at a substantial redshift—questions that have been addressed in the last few years by Persic & Salucci (1992) and Fukugita, Hogan, & Peebles (1998), as far as baryons are concerned, and including metals by Pettini (1999), Pagel (2002), and Lilly, Carollo, & Stockton (2004). Table 1.2 is based on work by Finoguenov, Burkert, & Böhringer (2003), whose numbers I quote with their kind permission.

While it has long been known that stars only account for a tenth or so of the baryonic matter density deduced from primordial deuterium and the cosmic microwave background angular fluctuation spectrum, there has been uncertainty as to where the missing baryons reside at present, although at $z = 2.5$ they are likely to be in the ionized gas associated with the Lyα forest. There is probably less such gas around today, much of the remainder being associated with O VI gas, which also contains like half the metals, assuming 0.2 solar abundance (the metal density is somewhat more robust than the baryon density, according to Mathur, Weinberg, & Chen 2003); the other half is mainly in stars.

Pettini (1999) drew attention to the fact that, while a quarter of all stars had been born by a redshift of 2.5, it was not possible to account for the corresponding quarter of today's metals on the basis of damped Lyα absorbers, Lyman-break galaxies, or the Lyα forest. This has given rise to two bold, but possible hypotheses involving dust in SCUBA galaxies (Dunne, Eales, & Edmunds 2003) and the arguments of Finoguenov et al. based on non-evolution of intracluster gas and its metal content since $z = 3$; so together these two sites might account for the bulk of the missing metals. Finoguenov et al. argue for early enrichment of the intracluster/protocluster gas by a top-heavy initial mass function. I am not sure if this is necessary; the issue may be decidable from the sort of data presented by Michael Loewenstein. In any case, the numbers in the table indicate an average yield for the whole Universe of about twice solar, similar to what one can get from a conventional Salpeter mass function.

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