Chemical Abundances in the Universe:
Connecting First Stars to Planets
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A Summary and Some Concluding Remarks

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1. Summary

To present a summary of IAU Symposium 265 it is perhaps best to first step back and ask the question "Why did we meet in Rio to discuss chemical abundances?". Part of the scientific rationale was to host a meeting that brought together researchers who probe chemical abundances and chemical evolution in all of the different astrophysical environments. All meetings should be planned such that they have an outcome and, with such a diverse set of abundance specialists brought together in one place to talk about their favorite topics, the stated outcome for IAUS265 was to provide, within our current understanding of the universe, a unified picture of the production of chemical elements over cosmic time; such a view is what I think of as cosmochemistry.

This broad goal of IAUS265 was nicely framed near the beginning of the meeting week by two review lectures: one was an Invited Discourse by Simon White entitled "Evolution of Structure in the Universe", while the other was the Plenary Review for IAUS 265 by Stan Woosley entitled "Origins and Evolution of the Elements". These lectures could be paraphrased, albeit too simply, as the formation and evolution of spatial mass structure and the formation and evolution of chemical structure. Taken together, the excellent reviews by White and Woosley illustrate how intimately related are the increasingly complex gravitational structure and chemical evolution of our universe.

As envisioned by the meeting organizers, the following 4 days of presentations spanned the entire spectral range of chemical studies from the very early universe down to the present day. These proceedings are the printed record of the presentations and indeed satisfy the stated goal of IAUS265 in providing an up-to-date picture of the origins and evolution of the chemical elements across cosmic time. In thinking about the connections between the early universe and the present-day universe, I categorize the meeting topics into four broad areas and briefly note some thoughts about each.

1.1. *The Early Universe and the First Stars*

As befits its important role as one of the pillars upon which rests our picture of a "Big Bang cosmology", Big Bang nucleosynthesis (BBN) was the first topic and we were reminded that it remains an important probe of the early universe, as well as non-standard physics. Predictions from BBN with 3 families of neutrinos are consistent with the results from studies of the Cosmic Microwave Background and with the observationally measured abundances of ^{2}H, ^{3}He, and ^{4}He. The currently measured abundances of ^{7}Li in the most metal-poor stars, however, do not agree with what is predicted from the CMB. This difference could be due to some process that is removing ^{7}Li from the atmospheres of the halo stars (such as unknown types of mixing or diffusion) or to perhaps new physics.

As if to enter on–cue in response to the ^{7}Li – CMB discrepency, the possible detections of ^{6}Li in metal-poor turn-off stars may provide the clues needed to solve the ^{7}Li mystery–if the observers are really measuring lithium-6! Since the detections of ^{6}Li rest on accurately mapping a rather small, red asymmetry in the much stronger ^{7}Li doublet, the discussion of lithium-6 led quite naturally into the topic of 3d model atmospheres and the limits of using 1d models. Since the 3d models with convection produce spectral lines with small red asymmetries, the question as to how much the ^{6}Li detections might be affected by this remains under active discussion.

Moving along in time, the meeting turned to discussions of the first stars. Due to a lack of cooling processes at zero metallicity, the expectation is that the very first stars should define a mass function that is strongly biased towards higher masses, perhaps with some extremely massive objects inhabiting the universe at this time and driving reionization. At such low metallicities, approaching the limit of no heavy elements, it was noted how stellar rotation may have a major affect on early nucleosynthesis and thus the initial phases of chemical evolution.

The increasing fraction of carbon enhanced metal-poor (CEMP) stars with decreasing [Fe/H] is a relatively new result and may be providing us with clues about some of the early massive stars that dominated chemical yields at this time.

1.2. *Chemical Evolution in the High Redshift Universe*

Thanks to the current generation of large-aperture telescopes (6.5m to 10m), distant faint objects with redshifts having z∼"several" can have their chemical abundance patterns scrutinized. The types of objects that are being probed at high-z include QSOs, Lyman break galaxies (LBG), damped Lyman-α systems (DLA), Lyman-α forest gas, or the ISM within the host galaxies of gamma-ray bursts (GRB). These objects are providing a wealth of chemical information about the universe when it was much younger and nicely complements the results from the nearby, but very old, low-mass stars. The gas size scales that are sampled by these different objects also vary over a wide range, with the QSOs being quite small spatially ($\sim$ tens of pc), while an ever-increasing spatial scale is provided by the LBGs, then the DLAs, and finally the Lyman-α forest systems, which span the largest scales ($\sim10^5$ pc).

We now know that in some of these objects, particularly the QSOs, chemical enrichment occurs rapidly, with many quasars containing gas with super-solar metallicities. There is evidence that in many of these systems chemical enrichment took place very early in the history of the universe, at equivalent redshifts of perhaps z∼9-10.

The range of conditions that can be probed using the variety of high-z objects is providing information on how SN feedback affects chemical evolution, as well as the importance of the AGN phase of a galaxy in shaping its heavy-element enrichment. These processes as they occur in young galaxies may influence the relation between central black hole mass and the inner galaxy environment.

1.3. *Mass Assembly and Galaxy Formation*

Chemical abundance distributions are providing new insights into how galaxies form and evolve. We are now able to probe chemistry in a growing variety of galaxy types, such as our own barred spiral, along with a number of smaller irregular and dwarf spheroidal galaxies. The abundance patterns in these smaller galaxies differ significantly from what is observed in the Milky Way disk and halo, with these differences telling us how star formation and the return of metal-enriched gas back into the local ISM varies in different types of galaxies. The distinctive abundance patterns being found in small galaxies can be used to constrain what types of objects may have been incorporated into the Milky Way halo. Of considerable interest are the newly discovered ultra-faint dwarf galaxies and whether there is any relationship between these tiny systems and the Galactic halo.

Continuing and increasingly sophisticated studies of the different components of the Milky Way, such as the thin disk, thick disk, inner and outer halos, or bulge and galactic center are painting an ever more detailed picture of our home galaxy. For example, there may be evidence now that the thick disk and bulge are chemically indistinguishable. It is also clear that there is substructure in the halo, with there being an inner and outer halo having different abundance signatures. Within the halo stellar "families" have been identified, via so-called "chemical tagging", which can be associated with parent galaxies, such as the captured system ω Cen or the Sagittarius dwarf galaxy.

To incorporate all of these new abundances from several galaxies into a coherent view of chemical evolution requires more complex models, which include both chemistry and dynamics. Processes such as infall or outflow must be modelled, as well as the dynamic interactions between different parts of a galaxy. These chemo-dynamic models are the tools with which we can improve our interpretations of the observed abundance patterns.

1.4. *Extrasolar Planets and the Chemical Connection*

The topic of "exoplanets" is a relatively new addition to cosmochemistry, but will be an increasingly important one in the coming years due to the clear correlations between the liklihood of the presence of large planets with host-star metallicity. Such chemical correlations in certain types of planetary systems may shed light on the relative importance of planet formation via core accretion or disk instability.

The possibility of interactions between parent stars and their planetary families (such as injestion of the planet by its host star, or the process of planetary formation) which may influence stellar chemistry is of interest. If it turns out that the presence of an underlying terrestrial-like group of planets can be gleaned from an accurate measurement of the stellar abundance distribution, the impact on our field will be enormous.

2. Concluding Remarks

After listening to all of the talks and the discussion, I came away from the meeting with a few impressions that are summarized below.

— As a group of researchers, we are literally awash in observations compared to not that many years ago. There are also impressive theoretical and modeling tools to help interpret our observations. The picture we have put together of cosmochemistry continues to grow in detail, with more connections between what were once thought of as disparate fields. I believe that we know much better now how the universe has chemically evolved from early simplicity to ever-growing complexity. But we are on the verge of painting an even bigger and much richer picture over the coming decade.

— Current large-scale surveys, and planned even larger surveys, will require management skills in order to efficiently exploit this new knowledge: good archives with uniform data sets, visualization tools, and improved communication. Such management skills are not necessarily required in small projects with just a few people, but the large surveys are really complex missions that demand more planning and more teamwork. Our needed set of skills is evolving.

— To maximize the science that can be extracted from the chemical abundances that are derived from the spectra that we gather and will gather, we must continue to push on improvements in the analysis. Many talks during the meeting emphasized this, with demonstrations of improved stellar abundance analysis techniques that may take us well below the 0.10 dex limits that many of us seem content to work within, down to less than 0.05 dex or even approaching 0.01 dex! 3d modeling, NLTE, inclusion of magnetic fields, rotational effects – a lot more physics involved in the analysis of the beautiful data sets that continue to be collected.

— Finally, on the horizon are the ELT projects, which currently number 3. These new telescopes will allow us to push back on all fronts and as a community we need more than one, ideally with sites in both northern and southern hemispheres and with first-light instruments that include high-resolution spectrographs. In whatever ways we can as a research community, we should be united in our support of these efforts.

I would like to take this opportunity to thank the organizers of this meeting, both for putting together such a varied and interesting set of sessions and for giving me the chance to present closing comments.