Putting the A-stars into context: concluding remarks

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1. Preamble

I want to thank the SOC for inviting me to give the final presentation, summarizing our conference. At the meeting I tried to mention all of the talks, and do my best to pronounce the speaker’s names. I appreciate the help I got. There is no need to review the presentations in these written final remarks. The reader may simply turn to the appropriate authoritative presentations themselves. Instead, we shall make a number of comments on aspects of CP star abundances, and our understanding of them from the prospectus of half a century’s efforts in this field.

2. Two areas

Before turning specifically to abundances and spectroscopy, I should like to express admiration for developments on the theoretical and observational fronts in two areas: pulsation, and magnetic/chemical mapping. Developments in these areas are formidable, amazing, and hold great promise.

3. The A-star puzzle

The chemically peculiar A- and related stars have been a puzzle for more than a century. In these remarks, we shall mostly discuss certain aspects of the chemistry of those CP stars known as HgMn or mercury-manganese stars. Among the CP stars, they have the simplest atmospheric structures, with minimal complications due to magnetic fields or convection. At the same time, their abundances show the most extreme deviations from the solar pattern.

It was reasonable consider the largest anomalies first. In attempting to understand any set of observational results, it is wise to begin with the extreme cases. Once they are understood, hopefully, the intermediate ones will fall into line.
The diffusion theory introduced by Georges Michaud (18) and the Vauclairs (cf. Vauclair, et al. [35]) was immediately seen to be able to account for abundance anomalies. It explained the overall patterns, which have the light, abundant elements depleted and the heavier, more rare ones in excess. It was soon shown to account for even the most extreme anomalies, ca. 6 dex, in a time as short as a million years. Already by the mid 1970’s there were papers written to account for isotopic anomalies in helium and mercury.

One might conclude, from the lack of recent efforts on the extreme and most bizarre (e.g. isotopic) anomalies that this area was well understood. This is not the case.

4. Credit where it is due

Before proceeding with specifics, it is well to give credit to a few abundance workers upon whose efforts we draw. The field is dominated by papers of Adelman (see [1], [2] and papers referenced), Ryabchikova, and their coworkers ([24], and [23]). Kudos are due to Dworetsky and Keith Smith for a large body of work notably with the IUE spectra ([29], [28], [10]). As a result of these truly monumental efforts, we now have a clear idea of the range of abundance variations, from element to element, and from star to star. This work built on the qualitative but nevertheless excellent work of Bidelman [5].

We also note the relatively recent discovery by Castelli and Hubrig (7) of the rare isotope of calcium, $^{48}$Ca. It is not well understood how this nuclide exists in nature at all (cf. Clayton [8]), much less why it has been identified in stellar spectra. It is observed in both magnetic and HgMn stars, and appears to be the dominant isotope in HR 7143.

On the theoretical side, Georges Michaud has earned and received wide recognition for his work. We are pleased to be able to add our own accolades, to him, the Vauclairs, Georges Alecian, and their coworkers (cf. Alecian, et al. [4]). If their enormous efforts have not yet completely solved the problem of CP star abundances, they have provided the solid background for a solution.

Very fine observational and theoretical work has been carried out by workers whom we have no space to mention individually. We offer our apologies.
5. Confrontation with observations

The early theoretical work relative to HgMn stars gave predictions of many elements (cf. Michaud, et al. [20]). Attention was focused on the atmospheres and outer stellar envelopes.

Since the late 1990’s diffusion has been integrated into evolutionary calculations for complete stellar models. Ironically, the level of accuracy acceptable for the most of the models, was not achievable for the outermost atmospheric layers—with temperatures below about 200,000K (Turcotte & Richard [33]). We currently await results with a realistic treatment of atmospheres and microscopic physics for these regions (cf. Stift & Alecian [31], and Alecian, et al. [3]).

We predict that the new results, when they come, will not be qualitatively different from the old ones. There will still be a need to slow the diffusion mechanism down, and prevent abundance excesses much larger than those observed. If this prediction is correct, the ad hoc turbulent diffusion coefficient $D_T$ will still be needed.

In the modern, extensive work on Am/Fm stars, the region with temperatures below 200,000K is assumed to be thoroughly mixed. Chemical separation takes place in deeper layers, where simpler approximations, e.g. LTE, and a coarser opacity grid, are acceptable. So far, the results have been judged promising, though significant problems remain. However, the AmFm stars do not have extreme anomalies of heavier elements.

Observers know, on the other hand, that among the non- (or mildly-) magnetic HgMn stars, abundance ratios can vary significantly from one star to another. Abundance differences occur even between stars with similar temperatures. For example, on the iron peak, the star 53 Tau has a large (2 dex) manganese excess. Indeed, the Cr-Mn-Fe triplet itself shows a non-nuclear, odd-Z anomalous abundance pattern (see [28], and papers referenced therein).

However, the Hg abundance in 53 Tau is virtually solar, nor are there the P or Ga excesses often seen in HgMn stars. Mu Lep, with nearly the same temperature and Mn excess has overabundant P and Ga, and is overabundant in mercury by some 5 dex.

Why, while diffusion processes were creating the Mn excess in 53 Tau, did they not cause other excesses typical of HgMn stars, such as Hg, P, or Ga?

A useful case concerns a star whose unusual abundances were unknown.
a decade ago, HD 65949. This star may have the most extreme mercury overabundance known. The elements Pt, Os, and Re are in excess by 5 to 6 dex. The expected depletions of the light elements O and C are not seen, though N is deficient by 2 or more dex. This star has about the same effective temperature as κ Cnc or HR 7143 but it’s Mn abundance is less than that of those stars by 1.5 to 1.8 dex (cf. Cowley, et al. [9]).

Surely a complete understanding of the chemistry of the HgMn and related stars will explain not only the extreme abundances, but also why, in the same stars, other groups of elements have relatively unfraccionated patterns. The sophisticated examination of radiative support of Hg by Proffitt et al. [22], like that of Michaud, Reeves, and Charland [19] before it, treated only Hg or its isotopes. This was also the case for the study of Sapar et al. [25].

It is essential to check the wider consequences of any model. For example, we mentioned that even the small fraction of the heavy isotope $^{48}\text{Ca}$ present in nature is problematical. But it is easy to set up neutron-rich, nuclear quasi-equilibrium conditions that would lead to the meteoritic $^{48}\text{Ca}/^{40}\text{Ca}$ ratio. The problem is that this model would lead to other isotopic abundances that are not observed in nature. For our stars, it is thus essential to ask what might be happening to other elements while the atmospheric conditions are such that subtle isotopic fractionation can be taking place.

6. A token search for order

Let us consider two simple scenarios for the development of abundance anomalies in CP stars. In both cases, the initial abundances are solar, but in the first case the anomalies develop very rapidly and reach an equilibrium so that intermediate patterns are rarely seen. In this case, differences in abundance patterns would be seen in stars with different temperatures. Those with the same temperatures should have similar abundances.

In the second case, we assume abundance anomalies develop over time. In this case, stars with similar temperatures should fall into sequences, with the youngest (or those with the least chemical differentiation) at one end and the oldest at the other. One should be able to put the spectra in order, much as astronomy students sort stars into the temperature sequence by the appearance of their spectra.

Table I gives logarithmic abundance differences from the sun for four
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Table 1. Abundance data [El]

| Star    | T   | [P] | [S]  | [Cr] | [Mn] | [Fe] | [Hg] |
|---------|-----|-----|------|------|------|------|------|
| 46 Aql  | 13000 | +1.5 | −1.8 | −1.5 | +0.8 | +0.6 | +3.8 |
| HD 65949 | 13100 | +1.5 | −1.0 | +0.5 | +0.6 | +0.5 | +6.3 |
| κ Cnc  | 13225 | +1.8 | −1.0 | +0.1 | +2.4 | −0.2 | +4.9 |
| HR 7361 | 13300 | +2.0 | −1.0 | +0.2 | +2.5 | +0.1 | +4.4 |

Table 2. Abundance Sorts

| by P   | by S   | by Cr  | by Mn  | by Fe  | by Hg |
|--------|--------|--------|--------|--------|-------|
| 46 Aql | 46 Aql | 46 Aql | HD 65949 | κ Cnc | 46 Aql |
| HD 65949 | κ Cnc | κ Cnc | 46 Aql | HR 7361 | HR 7361 |
| κ Cnc | HR 7361 | HR 7361 | κ Cnc | HR 65949 | κ Cnc |
| HR 7361 | HD 65949 | HD 65949 | HR 7361 | 46 Aql | HD 65949 |

HgMn or related stars. All values are from the second spectra (first ions), from [24], [9], and [30]. The effective temperatures are similar though in Castelli’s [6] recent analysis 46 Aql has $T_e = 12560$ K. Numerical values are in the usual bracket notation, and rounded to one decimal.

In Table 2, the stars are sorted by increasing abundances of the elements in the column headings. So, for example, 46 Aql has the least enhanced phosphorus (P), and HR 7361, the most. The stars κ Cnc and HR 7361 might be called classical HgMn stars, and their abundances are similar. The other two stars are distinct from this pair, and from one another.

It is impossible to explain the varying orders of Table 2 in terms of a simple model where all stars begin with a solar abundance, and rapidly differentiate to a uniform abundance pattern. Naively, one might think from Table 2 that 46 Aql was the least chemically differentiated—the least mature–of the four stars. But it is the richest in Fe. Moreover, its S and Cr show significant depletions.

Both 46 Aql and HD 65949 are highly differentiated, but in quite distinct ways. It is difficult to see how, given time, one abundance pattern would evolve into the other. If time is the significant factor, we can ask which elements begin to show their anomalies first. We see no clue to a temporal order in the tables presented here. A more complex scenario is
7. Other peculiar stars

7.1. Cobalt stars

One hears almost nothing of the cobalt stars, whose extreme members are found in the magnetic CP sequence. Some of these stars have Co/Fe ratios greater than unity: HR 4950, HR 1094, HD 200311 (cf. Nishimura [21]). The triple Fe-Co-Ni shows an odd-Z anomaly reminiscent of the Cr-Mn-Fe pattern seen in some manganese stars. These anomalies surely arise by chemical separation processes. Why are they so rare? What unusual processes might cause the enhancement of cobalt rather than manganese?

7.2. Lambda Boo stars

There was little beyond the brief mention by Landstreet [15] about the λ Boo stars at our symposium. Was that because our main tool for understanding CP stars can’t help us with these stars? For the typical diffusion pattern is a depletion of the abundant lighter elements with an excess of the rarer, heavier ones. Overall, this fits most CP stars rather well. But the λ Boo stars have the opposite pattern—normal lighter elements with depletions of the heavier ones.

Still, diffusion must be relevant! As has been emphasized many times, the mechanism is fundamental and must work. No one has suggested the atmosphere/envelope of the λ Boo stars is convective! What has been suggested is that grain-depleted gas has somehow been added to their surfaces. This hypothesis predicts a depletion of refractory elements, but not volatile ones.

This λ Boo hypothesis has a serious flaw. The volatile element zinc (Zn) is depleted in those stars where its abundance has been determined. This has been known for some time, but is rarely discussed (cf. Heiter [12]). Could diffusion account for this? We note here that the Zn abundance is one of the most highly variable among the CP stars. In the HgMn star χ Lup, it was found to be depleted by some 4 orders of magnitude (Leckrone et al. [16]). But Zn is generally found to be significantly underabundant in most HgMn stars (Smith [27]). If it fell on a stellar photosphere, would it diffuse quickly away?
8. Exogenous processes

Forty years ago, the notion of material falling on a main-sequence star was regarded as virtually impossible. Today, we know it happens. We have seen spectacular images of comets or asteroids being devoured by the sun (cf. [34]). In most cases, events like that cited are of disruptions in the low corona, but Sekanina [24] discusses the plausibility of direct impacts. We also know that debris falls on white dwarfs. Indeed, atmospheric abundances in certain white dwarfs may give an indication of the nature of the circumstellar material (Gänsicke, et al. [11], Jura & Xu [13]).

There is gathering evidence that our sun itself may bear the complementary pattern to that shown by the metal-rich white dwarfs (Meléndez [17]). The most accurate solar/stellar abundances indicate the sun is depleted in refractory elements. This, essentially, is a subdued example of the abundance pattern already noted for the λ Boo stars–refractory elements depleted, volatile elements (apart from Zn) normal.

We are aware of debris disks about young and even mature stars. Could the puzzling star spot on α And have been caused by infalling material? (cf. Korhonen [14])

Mainstream theoretical efforts to understand CP abundances have been largely limited to endogenous processes, those taking place in the stellar atmospheres, interiors, or in winds. Accretion, mass transfer in binaries, and debris infall have not been included in detailed calculations. Some of these newly recognized phenomena might work well in synergism with chemical separation mechanisms.

Modern calculations show time-dependent abundance oscillations in stellar interiors (cf. Théado, et al. [32]). Could they introduce sufficient disorder to frustrate a time sequencing of atmospheric abundance patterns we sought in Section 6? The question is moot, but not a justification to eschew exogenous processes that we know are plausible.

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