THE ABUNDANCE CONNECTION - THE VIEW FROM THE TRENCHES

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Prologue

On Sunday morning, the day before our symposium opened here by the Black Sea, Georges Michaud asked me if I would be willing to be one of three speakers at this closing session. When he intimated that I was to be a stand-in for Wal Sargent who is unable to be here, I set aside all remnants of reluctance and agreed to entertain you for approximately twenty minutes. Wal was one of my earliest inspirations as I trod a path from solar physics into stellar spectroscopy.

1. Some Omissions

Casual inspection of the program for this symposium surely conveys an impression that *all* known stars and *all* physical processes relevant to *all* stages of stellar evolution have been discussed here. But omissions can be noted. Here, I comment on one or two.

1.1 WEAK G-BAND GIANTS

These peculiar G-K giants epitomize for me the frustrations one may face in solving puzzles in which 'the abundance connection' should provide the vital clues. Weak G-band giants, which were mentioned only briefly by two speakers, were first identified by the eagle-eyed Bidelman (1951): the G band of the CH molecule is extremely weak in spectra of these Population I giants whose spectra at classification dispersions appears normal in all other respects. Nearly 30 years were to pass before the chemical compositions of the weak G-band giants were first explored quantitatively - see Cottrell and Norris (1978) and Sneden *et al.* (1978).

These giants of approximately solar metallicity have atmospheres that are severely contaminated with CN-cycled material:

• carbon is deficient by a factor of 10 to 40;

• the $^{12}C/^{13}C$ ratio is close to the equilibrium value ($\simeq 3.5$) for the CN-cycle;

• nitrogen is overabundant such that the sum of ^{12}C, ^{13}C, and ^{14}N is conserved at the presumed initial value, as running of the CN-cycle requires;

• oxygen has an approximately normal abundance; *i.e.*, the ON-cycle has not run on the processed material.

These signatures are, of course, amplified versions of those seen in normal giants after the first dredge-up. I am unaware of a convincing theoretical explanation for the severity of the contamination. One must add another puzzling piece of data: some of the stars contain lithium. A few years ago, in a survey of Li in weak G-band stars (Lambert and Sawyer 1984), we showed that the Li abundances ran from $\log \varepsilon(\mathrm{Li}) \simeq 3.0$ (the stars' presumed initial abundance) to upper limits as low as $\log \varepsilon(\mathrm{Li}) < 0.3$. Association of Li with CN-cycled material raises several fascinating questions:

• Has Li been manufactured in (or near) the weak G-band star? Li production, as discussed at this symposium, is possible in a hot bottom convective envelope where ^3He is converted to ^7Be as the CN-cycle turns C to N. Li synthesis may even be possible in a He-core flash. We dismissed

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these possibilities, in large part, because they do not readily account for the fact that maximum Li abundance is equal to the star's initial value. We supposed the Li was not manufactured but preserved in these stars.

• How can the star's atmosphere be mixed with CN-cycled material and yet preserve up to 100% of its initial Li content? Even normal giants dilute their surface Li content by a factor of 40 or so as they experience a mild enrichment of CN-cycled material at the first dredge-up.

• Where are the progenitors and descendants of these stars?

• How, if at all, are these stars related to the Li-rich giants having normal (*i.e.*, post-first dredge-up) abundances of C (including ^{13}C), N, and O? The first example of a Li-rich normal giant was discovered by Wallerstein and Sneden (1982). A survey uncovered some additional examples (Brown *et al.* 1989). As for the weak G-band stars, the upper bound on the Li abundance is the primordial value log $\varepsilon(Li) \simeq 3.0$.

To answer these and other questions, I think it likely that observers must define even more fully 'the abundance connection'. In the light of Professor Ivanov's fascinating talk, we should search for clues to the temperature at which the CN-cycling occurred. He noted that Na production can occur at reasonable temperatures as ^{22}Ne is converted by proton capture to ^{23}Na. Is Na overabundant in weak G-band giants? At somewhat higher temperatures, $T \gtrsim 40 \times 10^6$ K, ^{25}Mg is depleted by proton capture to produce unstable ^{26}Al. If a major fraction of the CN-cycled material has been exposed to such temperatures, the Mg isotopic ratios will be peculiar. Fortunately, this prediction is open to test using the MgH A-X lines near 5140 Å that are present in the carbon stars. Moreover, the large underabundance of carbon means that the C_2 lines that blend with almost all of the most useful MgH lines are effectively absent. Some years ago, I took spectra of the MgH lines in southern weak G-band stars. I recollect that visual inspection showed no anomalies in the Mg isotopic ratios but I was expecting none! A thorough analysis is now warranted and the observations should be extended to the northern stars.

1.2 THE HE-CORE FLASH

As an observer, I entertain the suspicion that the He-core flash in a low mass star may induce mixing between the He-core and the base of the giant's convective envelope and, since the core material may be enriched in carbon from the 3α-process, the mixed star will appear carbon-rich relative to other giants. My suspicions are fed by a miscellaneous collection of abundance anomalies in giants at or above the luminosity expected for He-core burning ('clump') giants. On the theoretical side, I am a little surprised in this era of supercomputers that more attention has not been paid to hydrodynamical modeling of the He-core flash. I followed with interest the work of a few years ago by Deupree (1984) in which mixing from core to envelope did seem to be predicted. Can the simplifications and approximations of those calculations be improved upon now? I heard no one at the symposium comment on theoretical studies of the He-core flash.

Of the peculiar stars that might owe their birth to mixing at the flash, I would give pride of place to the early R or warm carbon stars. I cannot recall a reference to R stars during this week. These stars are giants with an absolute luminosity close to or above that of clump giants. Relative to normal giants, the R stars are quite obviously carbon rich and nitrogen rich. They appear to be C-rich in the sense that carbon is more abundant than oxygen: Dominy (1984) found the C/O ratios to be in the range 0.9 to 3 and the $^{12}C/^{13}C$ ratios in the range 4 to 9 (one star had $^{12}C/^{13}C = 15$). Oxygen (relative to iron) has a normal abundance. The heavy elements are not overabundant; the s-process did not run at the site that produced the excess carbon from the burning of helium. One other fact deserves a place in a summary of crucial properties of the R stars: the frequency of binaries among R stars is that found among normal G and K giant (McClure 1985). This contrasts sharply with the case of the Barium stars where all are binaries. Clearly, conversion of a normal star to a early R star is an intrinsic process, not the extrinsic (mass transfer across the binary system) process that creates a Barium star.

In my speculative scenario, the early R stars are born as a giant experiences an exceptionally violent core flash or a rare episode of mixing at the core's boundary. The selection rules for this birth are unknown. Severe mass loss prior to the flash? Rapid rotation in or near the core? After their birth, the stars must evolve along the AGB and retain their basic identity. Then, the stars seem likely to evolve into the J-type (^{13}C-rich) cool carbon stars such as Y CVn and T Lyr. High on the AGB, thermal pulses may lead to the dredge-up of yet more ^{12}C and, perhaps, of products of s-processing in the He-burning shell.

My suspicion that the He-core flash may convert a giant to a warm carbon star is fed in large part by the fact that there are *apparently* no dwarf or subgiant R stars. Today, one hastens to add that this stands in sharp contrast to the case of the Barium stars. The discovery of Barium dwarfs of spectral types F and earlier is a recent one. Now, one wonders if dwarf carbon stars may have been overlooked - it seems most unlikely. (I clearly recall a conversation a few years ago at an observatory dinner table at which two respected authorities on spectral classification insisted that the then lack of warm Barium dwarfs did not mean that there were none: "such stars would readily be misclassified as more luminous stars".)

Emphasis on the He-core flash as an agent for nucleosynthesis and the creation of surface abundance anomalies may be misplaced. Perhaps the flash's primary role is on occasion to drive mass from a star and so reduce the mass of the He-core burning giant. This speculation is lodged in my mind next to the few facts I retain about those RR Lyraes with near-solar metallicity ([Fe/H] $\simeq$ 0.0). Stars of solar metallicity with an initial mass of about 1 $M_\odot$ must shed 0.4 $M_\odot$ or so in order that the He-core burning star is placed in the pulsation strip. It is, of course, not demanded that this mass be lost at the core flash. Mass loss prior to the flash will suffice. One obvious question: What are the selection rules by which a star is chosen to spend its He-core burning days as a low-mass star in the pulsation strip rather than as a non-pulsating clump giant of about its original mass? One could imagine that the He-core flash determines those rules because it may be more sensitive to the input variables (mass, rotation rates, *etc.*) than is the mass loss rate from a quiescent giant or main sequence star.

Mention of the solar metallicity RR Lyraes brings to mind a puzzle concerning the oxygen abundances of RR Lyraes. Several years ago, Butler *et al.* (1986) derived O abundances from a non-LTE analysis of the strong O I 7770 Å triplet: [O/Fe] declined approximately linearly from 0.8 at [Fe/H] = 0 to 0.0 at [Fe/H] = -2. This decline is in sharp contrast to the variation seen in dwarf (and giant) stars where [O/Fe], which is 0 at [Fe/H] = 0, increases to about 0.5 at [Fe/H] $\simeq$ -1 and may show a slight increase in lower metallicity stars. Is the contrary trend of [O/Fe] with [Fe/H] in the RR Lyraes attributable to nucleosynthesis at the He-core flash or to a systematic error in the abundance analysis? The carbon abundance for the RR Lyraes (Butler *et al.* 1982) is, within the errors of measurement, identical to that reported for dwarf stars. Unless the C LTE abundance analysis is plagued by errors, it would seem that the core flash which is likely to manufacture more C than O cannot be manufacturing the excess O seen in the solar metallicity RR Lyraes. Further, more synthesis of O will not account for the O deficiency (relative to dwarfs of the same metallicity) of the metal-poor RR Lyraes. Has diffusion changed the RR Lyrae's surface composition? Since the metallicities of RR Lyrae in globular clusters agree with the metallicity of cluster giants, diffusion, if it operates must primarily change the oxygen abundance.

1.3 BINARY STARS

Binary stars received surprisingly scant attention here. Tutukov's customary comprehensive survey of theoretical work on binaries, mass exchange, and coalescence went unmatched with a similar review of observational studies showing how through mass exchange spectroscopic examination of the mass gainer and/or the mass loser can provide insights into 'the abundance connection'.

McClure's discovery in the early 1980s that the Barium giant stars were spectroscopic binaries gave us new ideas about the origin of these s-process enriched stars. Prior to his discovery, some including myself presumed that these stars were produced when a He-core flash went awry. No one entertained the idea that the Barium stars might be binary stars in which the s-process elements had been synthesized in a companion as it evolved along the AGB and then transferred via the stellar wind or a Roche lobe overflow to a much less evolved star to convert it to a Barium star. This simple proposal requires no exotic ideas and exploits the existence of AGB stars with s-process and C enriched envelopes. It took McClure's discovery to shake us up. Once we were shaken up, the expected similarities between the composition of the AGB S and C stars and Barium stars were found. Through loss of its envelope, the AGB star is reduced to a white dwarf. Although the detection of the white dwarf companion is at the limit of IUE, several detections of white dwarf companions confirm the mass transfer hypothesis.

In its broadest form, the hypothesis sets no constraints on the evolutionary stage of the mass gaining star at the initiation of mass transfer. Of course, one expects this star to be on or near the main sequence. Early discussions of the mass transfer hypothesis took note of the apparent absence of F-type Barium dwarfs. Bond's (1974) discovery of the CH subgiants partially filled the gap. The CH subgiants are spectroscopic binaries with a composition essentially identical to that of the Barium giants. Such subgiants extend to the main sequence, but appear to be no earlier in spectral type than about G0. As a result of several surveys, we now know that there are Barium dwarfs earlier than G0. This is comforting news for advocates of the mass-transfer origin for Barium stars. I was delighted to see Dr. North's poster describing the warmest ($T_{eff} \simeq 6500$ K) Barium main sequence star yet discovered.

Why did no one anticipate McClure's striking discovery and recognize that the puzzle of the Barium giants could be solved by postulating that they are binary systems in which the Barium giant was created by mass transfer? While this question may be left for the historians, I am concerned that the comparative neglect of binary stars at this symposium may lead us to repeat our earlier oversight: which of the outstanding classes of peculiar stars are better understood as binary systems that have undergone mass exchange or even coalescence? We should note that McClure's discovery was not serendipitous - see McClure (1985).

2. The Abundance and Evolution Connections

2.1 SYMBIOTIC STARS

Our reasons for pursuing 'the abundance connection' may be as diverse as our personalities. My interest in the pursuit is largely traceable to the opportunities offered for testing theories of stellar evolution through comparisons of the chemical compositions of stars from one stage of evolution to the next. On occasions, the comparison reveals how the abundances evolve as the stars progress from one evolutionary stage to another. On other occasions, the comparisons provide a check on our methods of abundance analysis. I shall mention an example or two of such comparisons that were raised this week.

Symbiotic stars went almost unnoticed here. These binary systems with a late-type giant and a white dwarf provide an emission line spectrum where the hot emitting gas is plausibly identified as material shed by the giant. Then, the composition of the hot gas, as deduced from the emission lines, and the composition of the giant's photosphere, as deduced from the absorption lines, are expected to be identical. Differences most probably indicate that systematic errors plague the emission line and/or absorption line analysis. I should also note that the emission lines provide information not obtainable from the absorption lines; for example, the He lines provide an estimate of the He abundance that is unobtainable from the giant's photospheric abundance. Nussbaumer *et al.* (1988) were the first to grasp the value of a comparison of emission and absorption line abundances. In our recent survey of M and S stars, we extended this pioneering work and noted that the C/O ratios of some symbiotics were lower than those of our M giants. I was interested here to see Dr. Schmid's poster paper in which his estimates of C/O for the symbiotics with the most reliable determination are close to our ratios for the M giants. (The emission line analysis does not give reliable abundances with respect to H so that one has to compare the C/O ratio, for example, rather than the C/H and O/H ratios individually. Similarly, the question of He enrichment has to be answered from ratios such as He/O and an assumption about the O/H ratio.) At present, our samples of field M giants and symbiotics contain no star in common. The next step will be the application of the two procedures to the same symbiotic. This test is in progress.

2.2 PLANETARY NEBULAE

In a most interesting review of the composition of planetary nebulae, Robin Clegg showed how their mean compositions differed between the Galaxy, the slightly metal-poor Large, and the even more metal-poor Small Magellanic Cloud. He showed that these differences were of the magnitude predicted by models evolved by Becker and Iben. To this confirmation of the theory of stellar evolution must be attached a qualification: the models referred to are of *intermediate mass* stars (3-8 $M_\odot$), but the vast majority of the AGB stars in the Clouds (and presumably too in the Galaxy) are *low mass* stars (< 3 $M_\odot$). No comprehensive theory exists for the third dredge-up in the low mass stars that are the most likely candidates for the progenitors of the majority of the planetary nebulae (see Sackmann and Boothroyd's review in this volume). I suspect that the comparison of the Galactic and Cloud planetary nebulae will prove to be a crucial test of the emerging theories of low mass AGB evolution.

The planetary nebulae like the symbiotic stars offer an external check on the abundance analyses of late-type (AGB) giants. It is, of course, necessary to assume that the ionized gas constituting the planetary nebulae has the same composition as the stellar photosphere of the AGB star. I could imagine that the ionised gas, the most recent ejecta from the central star, may not have quite the same composition as the AGB star. One would like to analyse the more extensive cool gas that often surrounds the ionized gas. The comparison of nebulae and stars can be done for only the few elements in common. Fortunately, C, N, and O are on this list and are the most interesting from the standpoint of 'the abundance connection'.

The C-rich and the O-rich nebulae would appear to test the analyses of the C stars and the M, MS, and S stars respectively. When the N and O abundances of Galactic nebulae from the disk are collated, it is seen that the data populate approximately a rectangle defined by log ε(N) = 9.0-7.5 and log ε(O) = 8.8-8.0. There is clear evidence that the predicted dredge-ups have performed as expected: a few nebulae are extremely N-rich and are among the most He-rich. One especially striking result is that the C-rich (C/O > 1) and the O-rich (C/O < 1) nebulae are *not* segregated in the N vs O rectangle. The stars populate a smaller rectangle that overlaps the former rectangle (say log ε(N) = 9.0-7.5 but log ε(O) = 8.8-8.5). In contrast to the nebulae the O- and C-rich stars occupy different regions: the C-rich stars span the range log ε(N) = 8.0-7.5 and the O-rich stars the range log ε(N) = 9.0-8.0.

Why are the C-rich and O-rich nebulae and stars so differently distributed in the N vs O plane? An attempt to account for the different distributions may wish to note the following possibilities:

- Of the O-rich AGB stars, some will evolve to become carbon stars before their conversion to a planetary nebula. Transformation to a carbon star may occur either by the dredge-up of carbon or by a hot bottomed convective envelope at $T \gtrsim 50 \times 10^6$ K in which C/O > 1 is achieved by equilibrium CNO-cycling. Others, however, will become planetary nebulae while they are still O-rich (*i.e.*, S) stars). Thus, carbon and oxygen rich planetaries occupy the space in the N vs O plane presently occupied by the O-rich AGB stars.
- The planetary nebulae created from the carbon stars will, of course, be carbon-rich unless the stars develop a warm ($T \lesssim 50 \times 10^6$ K) bottomed convective envelope before losing extensive amounts of mass so that the envelope can be reconverted by the CN-cycle to an O-rich one.

This account does not explain why the carbon stars are so N-poor. One might suppose they are metal-poor, but this supposition is not supported by the analyses of their metal lines. On discovering the different locations of O-rich and C-rich stars in the N vs O plane, my initial response was to suspect that the N abundances of the carbon stars had been systematically underestimated - see Lambert *et al.* (1986) for a discussion on the accuracy of the elemental abundances. The N abundances of the O-rich AGB stars seem more secure because identical results are obtained from the CN and NH lines, and the analyses of the M giants (post first dredge-up) give, as expected, the same abundance as their G and K giant progenitors. If the N abundance of the carbon stars is blindly raised so that the C-rich and O-rich stars are intermingled in the N vs O plane, another and equally striking problem is introduced: the lower half of the N vs O plane, which is populated by O-rich and C-rich nebulae, is rendered devoid of stars. New questions are introduced. Where are the stellar progenitors of the low-N nebulae? Is it a false assumption that the nebular material is to be identified with a stellar photosphere and envelope? If it is, how does the star destroy N in order to make a N-poor nebula that is not He-rich?

2.3 POST-AGB STARS

Howard Bond ably reviewed the composition of supergiants that are considered to be the evolutionary link between the terminal AGB star and a fully developed planetary nebula (PN) with its hot central star. In my opinion, his talk marks a deserved change in the establishment's view that the present metallicity is the star's initial metallicity. When metallicities in the range [Fe/H] $\gtrsim$ -2 were found, there seemed little reason to question the accepted view. (Clearly, it would be of particular interest to analyse the few post-AGB candidates identified as belonging to globular clusters in order to check that the derived metallicity is or is not identical to that of the cluster giants.) Since stars are predicted to evolve rapidly from the AGB to the PN phase, post-AGB stars should be rare. I recall that we worried about this issue in our paper on HR 4912 (Luck, Lambert, and Bond 1983). A cursory comparison with the number of RR Lyraes, stars of lower luminosity in a less rapid evolutionary phase, gave no reason for doubting the classification of HR 4912 with [Fe/H] = -1.2 as a post-AGB star.

When, however, we got to HR 4049 (Lambert, Hinkle, and Luck 1988), I became concerned about the implicit assumption that the metallicity could be identified as the initial metallicity. Now, Waelkens, Van Winckel, and Bogaert's poster reports that HD 52961 has [Fe/H] = -4.5. HR 4049 is similarly metal-poor: [Fe/H] = -4.4. If such metallicities are the original value and if the stars are in the brief phase linking the AGB and PNs, I would expect, as Howard Bond emphasised, that stars of this extremely low metallicity must be *very* numerous for the much slower stages of evolution, namely red giant and main sequence stars. Just as HR 4049 is in the *Bright Star Catalogue*, I would expect [Fe/H] $\simeq$ -4 giants in that catalogue. There are none!

There are other clues to be taken into account before the extreme Population II (*i.e.*, metal-poor) and post-AGB labels are attached to all of the recent discoveries for which the IRAS observations are largely responsible. These clues include:

• In general, the 'post-AGB' stars do not show the s-process enhancements seen in AGB stars such as the S and C stars. The high [C/Fe] ratios are interpreted as C enrichment from the third dredge-up. I indicated in my review that some calculations show the third dredge-up to put ^{12}C, but not the s-process elements, into the AGB star's envelope.

• The light elements C, N, O, *and* S do not share the metal deficiency. Indeed, their abundances are approximately *solar*; *e.g.*, HD 52961 has [X/H] = -0.3, -0.3, -0.4, and -0.9 for X = C, N, O, and S respectively (Waelkens *et al.*, poster). One can juggle the mixtures of H-burning and He-burning products to account tolerably well for the [C/Fe], [N/Fe], and [O/Fe] ratios, but sulphur is not so easily explained away as a product of nucleosynthesis when its 'metal' neighbors (*e.g.*, Mg, Si, Ca) share the deficiency of the iron group. Sulphur was first recognized as overabundant relative to iron by Bond and Luck (1987) in HD 46703. An approximately solar S abundance seems to be a general property of the metal-poor post-AGB stars.

• The compositions of the post-AGB stars are similar to those of the λ Boo stars which are disk stars on or near the main sequence. The post-AGB and λ Boo stars share another characteristic: an infrared excess arising from a circumstellar dust shell.

If a metallicity [Fe/H] ~ -4 to -5 is not the star's original value, how is one to account for such extraordinarily low values? Late on a Thursday night, the following wild ideas came to mind:

• Destroy the Fe-group via the s-process. The s-process seems to be the only way in which to deplete the Fe-group. This speculation runs afoul of the fact that the post-AGBs are *not* s-process enriched.

• The abundances as derived by standard methods are seriously in error and underestimate the metal abundances. Matters of atmospheric structure, opacity (is H the dominant influence on the continuous opacity?), and non-LTE deserve consideration. However, one would suppose that the spectra of HR 4049 and HD 52961 do indicate an extreme underabundance of the metals.

• Diffusion has been at work. For the case of the λ Boo stars, we were able to suggest that extant calculations could not account for the abundance anomalies (Venn and Lambert 1990). Appropriate calculations for post-AGB stars do not appear to have been reported.

• Separation of grains from gas. In pondering on the λ Boo stars, we were struck by the fact that the elements that were underabundant were just those that are underabundant in the interstellar gas and the elements (C, N, O, and S) that have near normal abundances in the λ Boo stars also have normal abundances in the interstellar gas; the underabundance is attributed to depletion of those elements in and on the grains. The correlation suggested to us that the λ Boo stars accrete circumstellar or interstellar gas, but not the grains. Then, until the accreted gas is mixed and diluted, the star shows the composition of the accreted gas. This idea or a variant (grains are expelled to create a metal-poor atmosphere?) seems worthy of consideration in the case of the post-AGB stars; for example, additional elements such as phosphorus should be investigated.

This last speculation sought to explain how a moderately metal-poor star could be transformed into a star with a very metal-poor atmosphere. I did not address the issue of evolutionary phase. I suppose that they may be post-AGB stars, but the lack of s-process overabundances requires that they have evolved off the AGB before thermal pulses and the third dredge-up commenced. Early departure from the AGB may be possible if the star commences AGB evolution with a thin envelope. I suspect that much could be learned from a survey for post-AGB stars in the Magellanic Clouds.

3. A Comment on Non-LTE

It was, I think, on Monday that observers engaged in abundance analyses were divided into men (and women, I would suppose) of today and men of "the ancient ages". As one who is physically of the latter class but keen to belong to the present, I hope I may be allowed to comment. The tools now applied in an abundance analysis were almost undreamed of just a few years ago: model atmospheres, spectrum synthesis codes, and the like are applied routinely to spectra of high quality. These advances on the astrophysical front have been matched by physicists and chemists working on atoms and molecules who are providing the needed basic data. When non-LTE calculations are performed, our appetite for that basic data swells.

'Modern man' practices non-LTE analyses of stellar spectra. 'Ancient man' adheres to the wonderfully simplifying assumption of LTE. There can be no doubt that non-LTE is a necessary approach: the escaping starlight whose spectrum we record and analyse signals that LTE is invalid. The appropriate question today is surely not one of principle but of practice. This question deserves a full discussion replete with examples drawn from current literature. This is not the place for that discussion but it may be useful to offer some general remarks. I make no claims that these are profound but I have discovered that young enthusiasts tend to forget or overlook some of these points:

• First, a survey of the literature will convince all but the most ancient of men that the practice of non-LTE has become highly developed and widely applied. We are fast approaching the time when a non-LTE abundance analysis will be the norm rather than the exception. I would note equations of radiative transfer and statistical equilibrium. I noted above the steadily increasing provision of the necessary basic data (f-values, collision strengths, *etc*.). The student wishing to pursue 'the abundance connection' must read this recent literature on non-LTE.

• Second, the student must recognize that no non-LTE analysis can yet be considered as unique. The solution presented depends on the adopted model atom (or molecule!), the radiative and collision strengths for transitions between levels of the model atom, and the adjacent ions. The rates entering into the equations of statistical equilibrium depend on these adopted strengths and on the radiation field in the stellar atmosphere whose calculation, particularly in the ultraviolet, depends on the treatment of continuous opacity and often on the line blanketing. I shall give an example to illustrate the non-uniqueness of current non-LTE calculations.

My example is drawn from hot stars: the case of the C II 4267 Å line in B stars. The first non-LTE study of C II was done by Lennon (1983) who found that the observed equivalent width of the prominent feature at 4267 Å was much weaker than both the LTE and his non-LTE predictions: the NLTE predicted equivalent widths exceeded the LTE values. Recent non-LTE calculations by Eber and Butler (1988) are close to the observed equivalent widths for the 4267 Å feature: these NLTE equivalent widths are less than the LTE values. The remaining small discrepancy between observations and predictions may be due to one or more of several factors, in addition to continuing inadequacies in the non-LTE calculation (model atom incomplete, *etc*.).

Why did the 1983 NLTE study fail to predict even the sense of the change to the LTE equivalent width for the 4267 Å line? It appears that the answer lies in the size of the adopted model atom rather than the differing treatments of specific transitions. Eber and Butler remark "there is no simple explanation for the different results of the current calculations compared with those of Lennon.... It would seem that the increased complexity of our model atom, compared to that of Lennon, is responsible for the improved results". Lennon's model C^+ atom consisted of 14 levels. Eber and Butler include about 100 levels. This example is offered as a cautionary tale and is not necessarily a fair measure of the potential reliability of non-LTE abundance analyses. If the C abundance in B stars is the goal, it should be derived from some of the many other C II lines that are much less sensitive than the 4267 Å line to non-LTE effects.

In view of the lack of uniqueness, it behooves providers of non-LTE abundance analyses to estimate the uncertainties due to the limited size of the model atom, the adopted collision strengths, the atmospheric model and its radiation field, *etc*. This is necessarily a difficult task, but essential.

• Third, considerable useful information can be gleaned from stellar spectra without a full non-LTE treatment. Two examples must suffice. LTE analyses may define quantitatively the magnitude of some non-LTE effects. Raffaele Gratton's poster on oxygen abundances of a sample of dwarfs and subgiants illustrates well this point. He used the [O I] 6300 Å and O I 7770 Å lines to show that the latter give a systematically higher abundance that is due presumably to non-LTE effects in the excitation of the oxygen atom affecting the formation of the permitted 7770 Å triplet, but not the forbidden line. Such an analysis shows where non-LTE rears its head and defines the magnitude of the effect, as long as the forbidden line may be presumed immune to non-LTE effects. Hence, Gratton's analysis offers the non-LTE enthusiast a well-defined quantitative challenge.

By analysing a peculiar star with respect to a standard star of very similar characteristics, the effects of non-LTE on the abundance analysis *may* be partially cancelled. The cancellation cannot be complete but, in some cases, it will be possible to make at least a semi-quantitative assessment of the residual non-LTE effects. I recall our analysis of neutral and ionized lines in the classical Barium star HR 774 and the standard star β Gem (Tomkin and Lambert 1983). Pairs such as Fe I and Fe II gave distinctly different abundances when each star was analysed, but these differences attributable to non-LTE effects cancelled when the abundances from individual lines were expressed as an abundance ratio of HR 774 relative to β Gem.

• Fourth, there remains a need for atomic and molecular data. I would here note a crucial lacuna in the data needed for NLTE calculations for cool stars. Collisional transfers between levels of a model atom are assumed - often implicitly - to be achieved by collisions with free electrons. In cool stars, hydrogen is neutral and electrons are provided by the much less abundant metals. Hence, hydrogen atoms (or H_2 molecules) outnumber the free electrons by factors of 10^4 or more in cool photospheres of solar composition. Since the electrons and H atoms are thermalized to the same kinetic temperatures, one may reasonably wonder why the contributions of the H atoms to the excitation rates with the model atom are neglected. Two reasons would be advanced: (i) the collision rate depends on the thermal velocity and the electrons have a higher velocity by the factor $(m_p/m_e)^{1/2}$ or a factor of about 40; (ii) the cross-section for excitation by a slow moving H atom is expected to be much reduced relative to that for the electron (Massey 1949). The latter reason is a qualitative one, and not a guarantee that H atom collisions are a negligible contributor. Steenbock and Holweger (1984) included excitation (and de-excitation) by H atoms in a NLTE study of Li I lines using cross-sections estimated from a 'modified classical Thomson formula' (Drawin 1968, 1969).

This and other calculations by Holweger's group show that the H atoms cannot be disregarded in NLTE calculations for cool stars. It is clear, however, that the Drawin formula is a crude approximation (an 'order of magnitude estimate of collisional excitation and ionization cross-section'). Discussions with authorities in atom-atom collisions indicate that extensive and detailed calculations will be required in order to provide reasonable estimates of the cross-sections; it is unlikely that there is an equivalent expression to the van Regemorter formula used so widely for excitation by electrons. One can hardly expect to estimate cross-sections for particular transitions from analyses of the solar or stellar spectra in the way that these spectra provide 'astrophysical' gf-values on occasions. It is possible to estimate the scaling factor to be applied to a set of H-atom excitation cross-sections from a fit to a stellar or the solar spectrum and to then apply the scaled cross-sections to calculations for other stars.

• Fifth, other inadequacies of our current approach to model atmospheres and line formation may be as serious as the failure of the LTE assumption. This is certainly likely for cool stars. I would note that much needs to be done to ensure that the line blanketing, especially the contributions of the molecules, is fully represented in the model atmospheres and in the calculation of the synthetic spectra: Uffe Jørgensen's work at NORDITA on HCN, CN, C_3, and H_2O is an isolated example of a productive interplay of theoretical molecular physics and stellar astrophysics, One should also note other problems that are attracting attention: the 'bifurcation' of stellar photospheres when abundant molecules may induce cooling; the convective flows in cool red giants that may result in a photosphere broken up into a few large cells (some information on these convective flows is obtainable from line asymmetries, as was shown by Dr. Tsuji in his poster); dust may form close to the photosphere and produce some backwarming of the line forming regions. These and some other 'simpler' problems (*e.g.*, the substitution of spherical geometry for the conventional plane-parallel homogeneous layers) may well mask the predicted non-LTE effects as they are computed for a plane-parallel (or spherical) atmosphere of homogeneous layers in hydrostatic equilibrium.

Epilogue

Long after the scientific highlights of this fine symposium have merged in my mind with gleanings from the literature, I shall retain some memories of the persons who contributed to those highlights. Time and space, those wicked masters, mean that I must be highly selective here.

I began by saying that I was delighted to act as a substitute for Wal Sargent. It was Wal who in 1969 (I think) summoned me to a meeting in his office in the Robinson Laboratory on the CalTech campus to hear a young graduate student, Georges Michaud, explain his idea that 'diffusion' could account for the chemically peculiar stars. Now twenty years later, Georges has my admiration and respect for his brilliant intuition, his tenacity in developing his idea, and his applications of diffusion to a large area of the HR diagram.

At the meeting, I have been especially impressed by the many fine contributions by colleagues from behind the (former) Iron curtain - impressed but not surprised because I do read the translated journals. I was delighted by Professor Ivanov's talk on sodium enrichment. He began his model lecture by announcing that he was a newcomer to the field. New blood is essential. I award Dr. Ivanov the 'Newcomer of the Year' prize!

James Joyce, who might have confused even the cosmologists had he entered the field, once remarked that "Imagination is Memory". Our memory takes many forms. One aspect of our collective memory is the journals and books in our libraries. Reconsideration of observations recorded in journals may lead to novel results. Such is the case with the papers on He and N abundances in B stars that formed the core of Dr. Lyubimkov's paper in which he provided evidence that normal B stars become enriched in CN-cycle processed material as they evolve off the main sequence. I believe I simplify the story only slightly when I say that the original authors missed the effect extracted by Dr. Lyubimkov because they were content to quote a mean abundance. I award Dr. Lyubimkov the 'James Joyce' prize!

At the week's end, we must return to our telescopes and our computers. 'The abundance connection' is not yet understood in all respects. Before the story of stellar evolution is written and agreed to by theoreticians and observers, we shall pursue false leads, promote unwarranted speculations, and even commit a blunder or two. Let's not forget Fritz Zwicky's blunt advice to those who recognized a collosal blunder of their own making: "Then, you must come out of the trenches with your hands up"! I hope my views from the trenches have entertained you on this Friday afternoon. May we write the story of stellar evolution by toiling in the trenches, but be willing as necessary to scramble to the surface with our hands up.

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