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Model Atmospheres and Stellar Abundance Analysis

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Abstract

Model atmospheres have now been used in the analysis of stellar abundances for more than 50 years. During this period, remarkable progress has been made in the understanding of the physics of stellar atmospheres and in their modeling. The advances made in the observation of stellar spectra are even more remarkable. The question addressed here is whether comparable progress also can be found in the accuracy of the resulting abundances. It seems that this is *not* the case to the extent one might have expected, and the reasons for this are discussed. A number of recent developments in model atmosphere construction and in basic atomic and molecular data may, however, suggest that we are now approaching a situation with significantly diminished systematic errors in stellar abundances.

1.1 Introduction: A Bird's-Eye Perspective with Bibliometrical Comments

Bengt Strömgren's (1940) classical paper "*On the Chemical Composition of the Solar Atmosphere*" introduced the model atmosphere technique in the analysis of stellar abundances (for some brief historical remarks, see, e.g., Aller 1960). However, it took some time before the method became common practice, in particular for late-type stars. Most probably, this reflected the complicated task of calculating model atmospheres and the uncertainties in observed equivalent widths and gf values, which then contributed significantly to the total errors in abundances. A simple search in the NASA ADS database shows that the number of analyses with models started increasing very considerably around 1970 (see Fig. 1.1). Obviously, the existence of "grids" of model atmospheres (Carbon & Gingerich 1969; Gustafsson et al. 1975; Kurucz 1979; etc.) considerably facilitated this development. Other equally important factors were new measurements and compilations of more accurate gf values (Blackwell et al. 1980; Wiese & Martin 1980, and references therein) and new efficient spectrometers with detector systems with linear response (Reticons, CCDs). Presently, on the order of 200 papers are published each year with abundance analyses based on model atmospheres and directly related topics.

The increase of papers found in the ADS with the words "model atmospheres" and "abundance" in the abstract of the paper is about 2% of all papers with "stars" in the abstract, and about 0.6% of the more than 700,000 papers in the database. These figures refer to the total number of papers published during the period 1948–2001, but we have found that the percentages per year have remained astonishingly constant since 1970, in spite of the huge increase of the total number of papers published annually. It is also interesting to see that

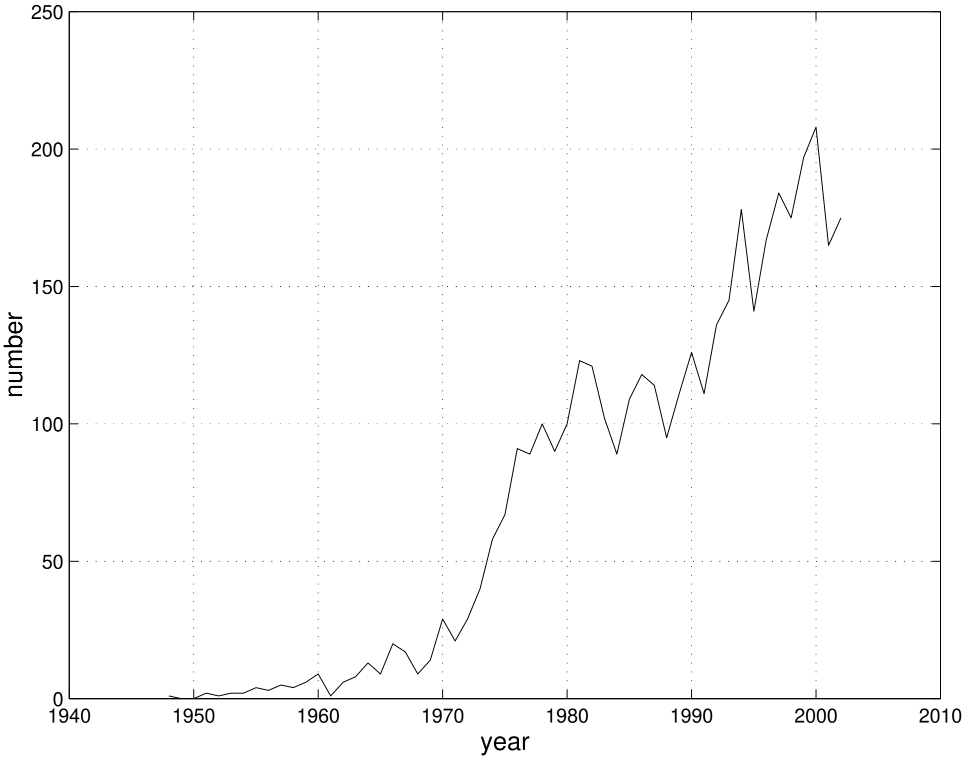

Fig. 1.1. Number of articles published per year with both "model atmosphere" and "abundance" in the text of the abstract, according to the NASA ADS database. The slower increase since 1980 may reflect the fact that the use of model atmospheres in abundance analysis had become standard by then, and hence why the word "model atmosphere" was not necessarily mentioned in the abstract.

the accumulated number of papers published since 1976 scales very well with the number of stars listed in the different editions of the Cayrel et al. catalog of field stars with [Fe/H] determinations (Cayrel de Strobel, Soubiran, & Ralite 2001, and references cited therein), which indicates that although many papers now each give abundances for many stars, this is compensated for by the fact that many papers contain analyses of stars for which some previous abundance determinations have already been made, maybe then only for iron or a few elements.

Another fact of some interest, at least when we have to deal with administrators and financing agencies, is the ratio of papers, again with "model atmosphere" and "abundance" in the abstract, relative to the total number of astronomers. If the latter is estimated by the number of individual members of the International Astronomical Union, we find a ratio that gradually increased from 0.8% in 1960 to 2.5% in 2000. In particular, there has been no tendency for the "productivity," measured in this way, to decrease during the latest decades. However, one should note that these crude measures neither give any indication of the very significant growth that has occurred in abundances published for new elements or for new types of stars, nor do they represent a great number of relevant papers without our key words in their abstract so that they were not caught in our crude search.

It is also interesting to see from which institutions the papers came. A simple comparison between affiliations of authors in 1970 and 2000 gave some clear indications. In 1970, more than 70% or the papers had authors from the USA. The others were mainly of French, German, British or Canadian origin. In 2000, the fraction of authors with US affiliation had diminished to 38%. For the rest, authors from the countries mentioned above still contributed significantly, but in addition to them astronomers from Spain, Sweden, Denmark, Japan and Australia, as well as a number of other countries, were active. A similar tendency is found within the USA, where astronomers from many institutions, not visible in the statistics for 1970, now contribute significantly, such as astronomers at Pennsylvania State University or University of Oklahoma. Also within the European countries this tendency is visible—e.g., in 1970, most of the papers were written by authors in Kiel and Hamburg. In 2000 authors from Berlin, Munich, Potsdam, Tübingen, and several other places also contributed. True enough, astronomy and astrophysics in general has been spread to an increasing number of places during recent decades. Still, I think it is a safe conclusion that the practice of abundance analyses has even spread more in the astronomical community during the last 30 years than many other specialties. It has become common practice; standard analyses do not require very specialized knowledge, due to generally available computer software for spectrum analysis, model atmosphere calculation and the derivation of abundances, and much easier access to suitable spectrometers.

This superficial overview, based on the ADS database, gives a rather healthy impression of a field in rapid expansion, which has now provided general and well tested tools for the study of stellar evolution, galactic history, and nucleosynthesis to the astronomical community. In what follows, we shall study whether this rosy picture is correct. We shall argue that further work is necessary if one wants to reach a level of accuracy in abundance analyses that in a reasonable way matches the development in observation technology and in the physical data on which the analysis is based.

1.2 Enormous Improvements—Better Abundances?

The techniques of abundance analysis of stellar spectra have developed immensely during the last 30 years. Thus, the largest telescopes provide more than a factor of 3 greater light-collecting area, the spectrometers with detectors are more than a factor of 50 more efficient, the volume and the quality of the required atomic and molecular data have improved by typically 1 or 2 orders of magnitude, the computers are more than a factor of 10^3 more rapid, the algorithms for some important types of calculations are more than a factor of 100 faster. One may also claim that the models are, as a result of the improvement in physical data and computing, more self-consistent.

The most obvious and most impressive of these developments is in spectrometer and detector technology, which has now made it possible to obtain high-resolution, high-S/N spectra for hundreds of thousands of stars, of a quality that was only obtained for the Sun and perhaps Arcturus and a few other stars 30 years ago. We shall here give some more detailed examples of further recent improvements, and then end the section with the question of whether these have contributed to significantly higher accuracy in abundances.

1.2.1 Examples of Improved Physics Data

Important new identifications and measures of wavelengths of spectral lines have been contributed in recent years. A good example is the laboratory work by Nave et al. (1994) and Nave & Johansson (1995), where 28 new energy levels were identified and 818 were revised, leading to about 4000 new identifications of Fe I lines, many in the near-ultraviolet and infrared and suitable as diagnostics in stellar spectroscopy. Wavelengths and energy levels were measured with high accuracy.

Line lists with f-values for atomic lines from the Opacity Project (Seaton et al. 1994) in the TOP database (Cunto et al. 1993) with more than one million lines mark a very considerable step forward in accuracy and consistency. The lists by Kurucz (1993), though generally less accurate, also mark a very important contribution, containing 25 times as many lines, including lines from very complex atoms. Other useful lists of line data, such as VALD (Kupka et al. 1999), NIST (Reader et al. 2002), and CHIANTI (Dere et al. 2001) are compiled according to different principles and contribute data for a variety of purposes.

The TOP database also contains photoionization data from the Opacity Project. The XSTAR database (Bautista & Kallman 2001) gives such data for iron from the Iron Project (Bautista 1997). These data are significant for the calculation of model atmospheres since bound-free opacities from elements like C, Mg, Al, Si, and Fe play significant roles in the ultraviolet spectral regions. Moreover, these cross-sections are important for calculation of the statistical equilibrium; photoionization affects the populations of different states in the atoms, and thus also the spectral lines.

For statistical equilibrium calculations, the cross-sections for atomic impact collisions with electrons and hydrogen atoms are still a major problem. Electron collision data may be found, for example, in the XSTAR database, but there is a general lack of reliable data for complex atoms and excited states. The hydrogen impact collision excitation and ionization rates for Li have recently been explored by Barklem & Belyaev (2004) and found to be significantly lower than the standard modification of Drawin's recipe.

Also concerning line broadening very significant steps forward have been taken in recent years. In particular, reliable damping data for collisions with hydrogen atoms have been calculated for many spectral lines by Anstee, Barklem, O'Mara, and Piskunov (see Barklem, Piskunov, & O'Mara 2000, and references cited therein). For Stark broadening, extensive work has been done by Dimitrijevic, Sahal-Brechot, and collaborators (see Dimitrijevic et al. 2003 for references). Improved calculations of Stark broadening data for hydrogen lines have been published by Stehlé & Hutcheon (1999).

Data for molecular lines are very significant for analyses of cool stars, both directly for the calculation based on a given model atmosphere of diagnostics in a spectral region, and indirectly for calculation of the structure of the model atmosphere. For the latter purpose global data are needed—the molecular opacity in general may be caused by millions of weak contributing lines. Also for the spectrum calculation the effects of molecular absorption, for example depressing the general spectrum around a particular diagnostics of interest, may well be due to a very great number of weak lines. Major contributions in calculating extensive molecular line lists have been made by U. G. Jørgensen and collaborators (1989, 1990, 1994, 1996, 2001) for CH, TiO, H_2O, C_3, HCN, and, more approximately, C_2H_2. Recently lists for CH_4 have been calculated (Borysow et al. 2004). Partridge & Schwenke (1997) have also contributed a line list for the vibration-rotation bands of H_2O with altogether 3×10^8 lines, and Schwenke (1998) and Plez (1998) produced almost as extensive lists for the numerous electronic bands of TiO. The situation for molecular data is thus much improved and has enabled detailed modeling of cool red giant atmospheres and spectra (e.g., Alvarez & Plez 1998; Allard, Hauschildt, & Schwenke 2000; Aringer, Kerschbaum, & Jørgensen 2002), but data for a number of important species, in particular polyatomic molecules, are still missing. Also, the existing data for several molecules, for example for water vapour in the near-infrared (see Allard et al. 2000; Aringer et al. 2002), are still not fully satisfactory.

1.2.2 Computers, Algorithms, Self-consistent Models

For his early calculations of line profiles with electronic computers, Heiser (1957) published some details on timing: the calculation of one single spectral line, represented by 15 frequency points and Voigt profiles in LTE, took 25 minutes on an IBM 650. With a modern work station we made the same calculation in 24 milliseconds, or about 60,000 times more rapidly. This agrees well with the famous Moore's law (Moore 1965), which suggests that the computer speed increases by a factor of 2 every 1–2 years.

However, in addition to this, the development of new algorithms for calculating radiative transfer in spectral lines and model atmospheres has been very important. A basic step forward was the development of the accelerated lambda iteration (ALI) methods for line transfer, by Scharmer (1981), Scharmer & Carlsson (1985), Werner & Husfeld (1985), Hamann (1986), and others, partly based on early work by Cannon and Rybicki. With these methods non-LTE problems may now be treated with thousands of atomic levels and transitions, as well as problems with velocity fields, partial redistribution, and in three space dimensions (cf. Auer, Fabiani Bendicho, & Trujillo Bueno 1994; Asplund, Carlsson, & Botnen 2003, and references therein).

The large number of contributing levels and spectral lines in realistic radiative transfer problems, not the least when model atmospheres are to be calculated, makes statistical representations necessary. Anderson (1989), Hubeny & Lanz (1995), and Hauschildt and collaborators (see Schweitzer et al. 2003, and references therein) have devised efficient schemes with "superlevels" and "superlines" for a consistent modeling of radiative transfer with non-LTE in heavy-blanketed atmospheres. For the calculation of the energy transfer in model atmospheres with complex spectra, a simple statistical method, called opacity sampling (OS), was developed by Peytremann (1974), Sneden, Johnson, & Krupp (1976), Ekberg, Eriksson, & Gustafsson (1986), and Helling & Jørgensen (1998). This is now used extensively for LTE model atmospheres; it is more flexible and easier to generalize to dynamical atmospheres and to non-LTE models than the previously used opacity distribution function (ODF) method. With the OS method and contemporary computers, LTE models with 10^5 frequency points, which is quite sufficient for a reliable representation of the radiative field through the model, may be calculated routinely.

A major step forward in the modeling of stellar atmospheres has been taken during the last two decades by Nordlund, Stein and collaborators (see Nordlund 1982; Stein & Nordlund 2000; Asplund et al. 2000a, and references therein), in calculating three-dimensional (3-D) models of convective atmospheres with consideration of radiation in some detail. Basically, the Navier-Stokes equations are solved in 3-D simultaneously with the equation of radiative transfer, assuming LTE (in most respects). The models tend to reproduce the observed stellar line shifts and line profiles with an astonishing precision (cf., e.g., Asplund et al. 2000b; Allende Prieto et al. 2002a), without relying on extra free fitting parameters like macro- and microturbulence, at least for solar-type stars. The models predict considerable temperature inhomogeneities in the stellar surface layers, which may severely affect the strengths of low-excitation atomic lines and molecular lines, and thus lead to strong revisions of abundances. Freytag is producing models of full stars—"a star in a box"—and concentrates on modeling red supergiants like Betelgeuse (Freytag 2003). His models are characterized by the appearance of very few huge "granulae," as proposed in a classical paper by Schwarzschild (1975). Gray (2001) has questioned the relevance of this result, on the argument that observed spectral line widths do not change very much with time. It remains to explore the observational implications of Freytag's models further, not the least for abundance analysis (see, however, Freytag, Steffen, & Dorch 2002).

Both for hot and cool stars with winds, very significant improvements have also been made. Spherically symmetric non-LTE models for hot stars with radiatively driven winds described by the hydrodynamic equations have been produced by the Munich group (Pauldrach, Hoffman, & Lennon 2001, and references therein). Models of hot stars, such as Wolf-Rayet stars and OB supergiants, with non-LTE radiation fields and with prescribed velocity fields have been calculated by several groups. These models often show good or satisfactory general agreement with observed spectra (see, e.g., the comparison between observed spectra of supergiants in the Magellanic Clouds and models published by Crowther et al. 2002), an agreement that suggests that fairly accurate abundances can be derived. For cool pulsating stars, the problems may be more severe, but a promising development is taking place. At least four groups are active in modeling atmospheres and winds of long-period variables [see, e.g., Wood 1979; Bessell, Scholz, & Wood 1996; Bowen 1988; Bowen & Willson 1991 (cf. also Willson 2000, and references therein); Fleischer, Gauger,& Sedlmayr 1992; Winters et al. 2000; Höfner & Dorfi 1997]. Höfner and collaborators (cf. Höfner et al. 1998; Höfner 1999; Andersen, Höfner, & Gautschy-Loidl 2003; Höfner et al. 2003; Sandin & Höfner 2003a, b) have produced self-consistent models with hydrodynamics, dust formation, and radiative transfer considered in detail. The spectra of these models clearly show much improved agreement with observed spectra, as compared with hydrostatic models or models with an oversimplified treatment of radiation. Also, the diagnostic power of emission lines of Mira stars are being explored in non-LTE calculations for dynamic models of the shocked outer atmospheres, with promising results (see Richter et al. 2003, and references therein).

1.2.3 Smaller Errors in Abundances?

Now, how are the improvements by orders of magnitude that have taken place in the underlying physics data and in observational data and computational resources reflected in the quality of the abundances derived? This may be studied by exploring how the abundance results and quoted errors have developed with time for certain stars. I have chosen two examples, the iron abundance of the archetypical extreme Population II star HD 140283, and the oxygen abundance of the Sun.

HD 140283 ($T_{\rm eff}$ = 5700 K, log g = 3.7, [Fe/H] = −2.4; Nissen et al. 2002) was one of the first stars analyzed—it is one of the subdwarfs studied by Chamberlain & Aller (1951) in their historic paper, laying the empirical ground for the view that nucleosynthesis is a stellar phenomenon. The first model atmosphere analysis of the star was made by Cohen & Strom (1968). The results of the different analyses of the star are presented in Figure 1.2, along with error bars when provided by the authors. We note that, in spite of the fact that the errors quoted have certainly diminished with time, the scatter between different determinations is

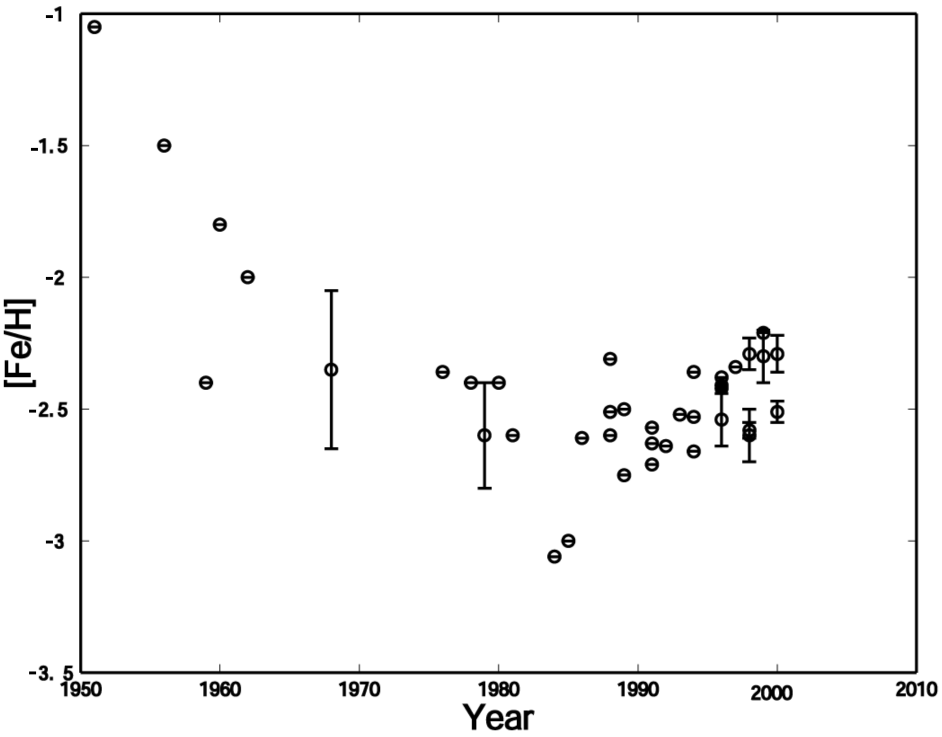

Fig. 1.2. The iron abundance determinations for HD 140283 as a function of time. Estimated errors are indicated when published.

still considerable and now significantly greater than the error bars given. It is questionable whether the scatter between different independent determinations has decreased during the last decades.

There are several reasons for this remaining scatter. One is the uncertainty in the effective temperature scale—the temperatures given still range from 5500 K to 5800 K. Another is uncertainties in convection or convection parameters when the mixing-length theory is used. Effects of thermal inhomogeneities in the surface layers, caused by convection, and departures from LTE in the ionization equilibrium of iron are treated differently in the most recent studies and also contribute to the scatter.

Determinations of the solar oxygen abundance are displayed as a function of time in Figure 1.3. The first point here represents the determination in the classical study by Russell (1929). We see that an initially large spread has decreased, but during the last 30 years a considerable scatter has prevailed. There is a tendency now for error bars to shrink very considerably, and the estimated oxygen abundance itself has recently decreased significantly. The scatter reflects the use of different criteria, and of different model atmospheres. The most recent results are those of Allende Prieto, Lambert, & Asplund (2002b) and Asplund et al. (2003). In the latter paper different criteria—the forbidden [O I] λ6300 Å line, the [O I]

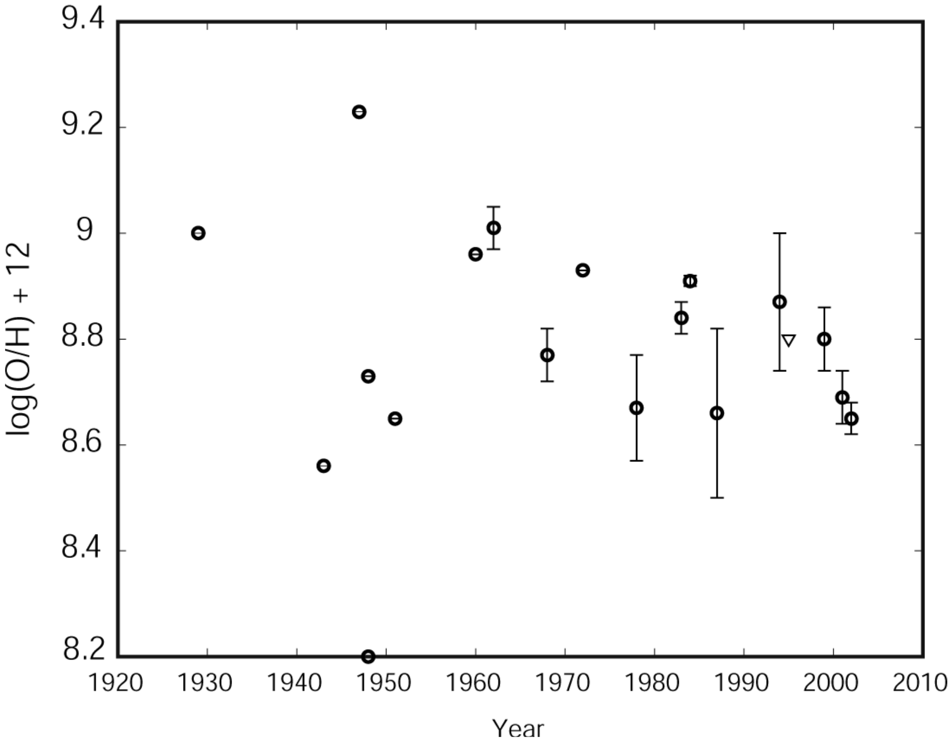

Fig. 1.3. Oxygen abundance determinations for the Sun, as a function of time. Estimated errors are indicated when published.

infrared triplet lines, and the vibration-rotation as well as the rotation-rotation infrared lines of OH—are all used, and give concordant results for a 3-D convective model atmosphere. The only remaining deviating criterion is that of the ultraviolet OH (A-X) lines—possibly deviating due to the effects of unknown opacity sources.

So, it seems that in spite of the general and considerable improvements in observations and modeling of stellar spectra, there is rather slow convergence in accuracy, as illustrated by these two examples. Against this conclusion one might advocate that the examples were chosen selectively—data for other stars might have shown more definitive convergence—or that the scatter admittedly has been great in the last two decades, but now, during the last two years, we are really improving (e.g., with 3-D models and non-LTE). In spite of the possibility that these explanations may be partly relevant, they certainly do not explain the full remaining scatter in the figures, nor the tendency for this scatter to stay roughly constant during recent decades.

Another possibility for the fairly constant scatter may be what I would call a "sheep-goat effect" (a term that I recently discovered is independently used, and with a different meaning, in parapsychology; cf. Lawrence 1993). The term "sheep effect" sometimes is used to explain the fact that different scientists tend to get rather similar results even if the systematic errors are severe, probably because they search for and eliminate systematic errors in their experiments and debug their computer programs only until they get the expected results. On the other hand, they may also welcome results that are not identical with those already published by others, in order to be able to contribute some new data, a behavior one may call a "goat effect" in its extreme form. The balance between these two, supposedly leading to a scatter in abundances on the order of 0.1–0.2 dex, is here called the "sheep-goat effect."

A less cynical and presumably more interesting explanation for the remaining and seemingly not very time-dependent scatter in the figures would be that severe systematic errors still remain in abundance determinations. Previous studies did not try to take these into consideration, so the earlier scatter reflects uncertainties in observed data, fundamental parameters, and standard model atmospheres, while some of the scatter that now shows up could be due to different attempts to handle convection, inhomogeneities, and non-LTE. In order to explore this possibility further, I studied error discussions in recent abundance analyses, and also approached a number of colleagues (many of them present at this Symposium) to find out of what systematic errors are considered most important, and what sizes these may have, in contemporary analyses. Here, the tentative result of this study will be sketched, without any detailed further references. It should be noted that the possible systematic errors due to non-LTE and inhomogeneities quantified below are still preliminary, and sometimes not much more than educated guesses.

In many papers, it is common to essentially limit the study of errors to those caused by uncertainties in fundamental parameters ($T_{\rm eff}$, log g, [M/H], etc). Errors of typically 0.1 dex in abundances relative to hydrogen and relative to the solar abundances are often quoted, both for early- and late-type stars, as a result of such parameter uncertainties, although for hot supergiants and for cool M and C stars errors twice as large are sometimes given (Gustafsson 1989). Errors in measurement, in defining the continuum in crowded spectra, and in relating stellar abundances to that of the Sun (e.g., by using lines that are saturated in the star or in the Sun) may typically sum up to similar amounts, in particular for stars very different from the Sun. Errors due to non-LTE in an LTE treatment, or caused by the uncertainties in collision cross-sections, may typically be estimated to 0.1–0.2 dex, both for early-type main sequence stars and for solar-type stars. Finally, errors due to inhomogeneities and 3-D convection are typically 0.1–0.2 dex for solar-type stars, while they may be 2 times larger, or possibly even more for certain elements, for Population II stars of similar temperatures. All these estimates are rough; the true values depend on whether the line is molecular, atomic, or ionic, and what its excitation energy is. In general, strongly temperature-dependent lines imply larger errors. Certainly, the type of star also matters—the more different the star is from the well-explored solar-type stars, the more uncertain are the abundances.

Let us take one example, being somewhat more precise. For metal-poor solar-type stars, as well as Population II giants, one may typically estimate the effective temperature to an accuracy of about 100 K, and the logarithmic surface gravity to about 0.2 dex. These uncertainties introduce uncertainties in metal abundances of about 0.1 dex, where the effects of the temperature uncertainty dominate for lines of neutral atoms that are not in the dominating ionization stage, such as Fe I, Li I, Mg I, or Si I. For lines of dominant species, such as Fe II, Be II, Ba II, etc., the error in gravity leads to similar abundance errors. Errors in defining the continuum level are relatively small in these stars, although there may be a problem with the opacity in the ultraviolet—either for these stars or for the Sun (cf. Bell, Balachandran, & Bautista 2001, and references therein; however, see also Allende Prieto, Hubeny, & Lambert 2003)—which could affect the accuracy of abundances relative to the

Sun and other metal-rich stars of Be, B and several other elements with useful spectral lines only in the ultraviolet, as well as nitrogen and oxygen abundances from the ultraviolet electronic systems of NH and OH, respectively. Another problem for the metal-poor stars is the very small number of lines of strength suitable for abundance analysis for many elements. Effects of departures from LTE have been studied for elements like Li, B, Na, and Fe I and found to lead to abundance corrections of typically 0.1–0.2 dex, and possibly more in some cases for metal-poor stars, primarily due to overionization by the strong ultraviolet radiation fields (e.g., Kiselman 1994; Gratton et al. 1999; Idiart & Thevenin 2000; Gehren et al. 2001; Takeda 2003; Christlieb et al. 2004). For abundance determinations from the oxygen triplet line there may be effects of similar size (Kiselman 2001). Finally, the effects of convective thermal inhomogeneities in the surface layers may strongly affect abundances determined from lines sensitive to the temperature, such as C, N and O abundances from the hydride lines, or abundances of Fe and other metals when determined from low-excitation lines of the neutral atom. Typical errors in such abundances, overestimated in standard analyses, may be on the order of 0.3 dex to as much as 1 dex (Asplund & García Pérez 2001; Asplund, private communication).

Obviously, we have about 3 to 4 different causes of systematic errors, each contributing uncertainties on the order of 0.1–0.2 dex, and for some abundance criteria and some stars even more. If these sources of error are not correlated or coupled—an assumption that may be doubtful (e.g., a positive feedback between convective thermal inhomogenities and photoionization is conceivable)—it thus seems realistic to ascribe uncertainties on the order of 0.2–0.3 dex to typical "absolute" abundances (i.e. relative to hydrogen and to the Sun).

1.2.4 Fortunately, Differential Studies are Better!

A very important fact, stressed for instance by Poul Erik Nissen at this meeting, is that abundance ratios such as [X/Fe] can be determined with much higher accuracy than absolute abundances, even with standard analysis using plane-parallel model atmospheres in LTE, provided that the abundance criteria are suitably chosen. For instance, one could base determinations of [Mg/Fe] or [Si/Fe] for solar-type stars on measurements of lines of Mg I, Si I, and Fe I. Similarly, [C/O] determinations could be based on highly excited lines from both atoms, with the expectation that systematic errors in fundamental parameters, model structure, and even in the ionization and excitation equilibria will cancel to a large extent. It is then important to try to use lines from both elements of about equal strengths and, if possible, excitation, so that the line contribution functions roughly sample the same layers in the stellar atmosphere. In general relatively weak (unsaturated) lines should be preferred since abundance values resulting from them are less dependent on the model structures and the atmospheric velocity fields (see Gustafsson 1983). Differential studies have indeed produced a number of significant and very interesting results on levels close to or below the systematic errors discussed above, such as the study of scatter in relative abundances by Edvardsson et al. (1993) and Nissen et al. (1994), as well as the interesting abundance differences between different populations at a given [Fe/H] found by Fuhrmann (1998, 1999), Nissen & Schuster (1997), and Feltzing, Bensby, & Lundström (2003; see also Bensby, Feltzing, & Lundström 2003 and Feltzing et al. 2004).

Another important fact to stress is that one may reduce the effects of systematic errors very considerably by intercomparing stars that are close in the $T_{\rm eff}$-log g-[Fe/H] space. For example, Nissen & Schuster (1997) find errors in [Mg/Fe] of only 0.03 dex in their comparison of thick- and thin-disk stars, errors mainly determined by uncertainties in measured equivalent widths. The extent to which differential studies of these types are free of systematic errors still remains to be explored. Two factors are obviously of significance here. The first is the extent to which the element of interest—Mg in the example mentioned—is just a "trace element," i.e. of no significance for the atmospheric structure. For cooler stars Mg may, for instance, be an important electron donor, thus affecting the continuous H^- opacity. Such a possible effect may easily be handled in a classical analysis by using model atmospheres tailored to be self-consistent with the results of the abundance analysis. The only worry is then that the effect could couple to systematic errors that have not been considered, such as non-LTE overionization of Mg, which could in itself depend on the Mg abundance. The other factor to consider is *how* close in the $T_{\rm eff}$-log g-[Fe/H] space stars have to be in order for the systematic errors to be reduced to unimportant levels. This question must be studied using more detailed model atmospheres, with the systematic effects (non-LTE, 3-D convection, etc.) modeled, at least schematically. An important question is then also whether more parameters than the classical trio, such as stellar rotation, mass, or age, are fundamental in determining the atmospheric structure and the spectrum.

One circumstance that is of major significance for accurate differential studies is the fact that spectrometers with high S/N and high resolution now provide a very wide spectral region in one exposure, so that optimal criteria can be chosen for accurate differential analyses. Also, different criteria can easily be used, and resulting abundances may be systematically compared.

1.3 Conclusions

We have found that there have been very significant improvements, by orders of magnitude when measurable, in most aspects of stellar abundance analysis. However, in absolute abundances there are still several types of systematic errors remaining, of at least 0.1 dex each and even considerably more, in many important cases. We have therefore advocated differential studies, as far as possible *strictly* differential between different but physically similar stars and different elements with similar types of abundance criteria, as being much more accurate.

The progress in 3-D convective models with radiative transfer, in non-LTE modeling of early-type stars with winds, in pulsating models of red giants with time-dependent radiative transfer and dust formation, in non-LTE models of cool stars where the statistical equilibrium equations are solved for many atoms and molecules and very many levels, has been brought to a stage at which detailed comparisons with spectra show very much improved agreements with observations as compared with standard, static LTE models. However, the fully *physically* consistent model atmospheres, with 3-D geometry, magnetohydrodynamics in full play, and non-LTE radiative transfer in satisfactory detail, still remain to be constructed.

Will it really be worth going to this degree of sophistication? There are different views expressed on this in the astronomical community. I would suggest that the answer is "yes," in view of the facts that the attempts and comparisons with non-classical models demonstrate systematic errors in absolute abundances that are as great as 0.1–0.2 dex or more, and that many new and interesting features in galactic abundance patterns have been disclosed in differential studies to exist at these levels or lower.

It seems that the theoretical development will within a decade lead us to a stage when standard analyses with static LTE model atmospheres will be looked upon as curve-of-growth analyses were regarded about 30 years ago—an old-fashioned tool that gives abundance indications but does does not match the quality of, and the effort behind, the observed spectra. This progress should not be worrying for the stellar spectroscopist—the effort in applying the new theoretical developments will hopefully be no greater than it was to apply classical model atmospheres about 30 years ago. Also, there is a much more constructive attitude to meet the complexity that nature demonstrates to us in the significant details of stellar atmospheres—these beautiful plasma "landscapes" also show phenomena of structure formation that may be related to the study of the origins of structure and complexity in broad areas of natural sciences, which may bring us, and our field, closer to interesting developments in neighboring fields. For the observer, this also means that many features in spectra, not only abundance criteria like the equivalent widths of certain selected lines, should be brought into the analysis for checking and challenging the models. These features will include line profiles and strengths of numerous lines with diagnostic power for the analysis of velocity fields, temperature structure, thermal inhomogeneities, magnetic fields, etc. The development of modern instrumentation has made this possible, or even simple.

In his fundamental paper *"On the Composition of the Sun's Atmosphere"* from 1929 Henry Norris Russell wrote:

> *The hope that from the familiar qualitative spectrum analysis of the solar atmosphere a quantitative analysis might be developed is of long standing. Recent developments in spectroscopy and astrophysics have turned the hope into rational anticipation. The most precise method of investigation—the study of the detailed contours of individual lines, promises the most, but it will be some time before it can be applied to the multitudes of lines available ...*

Russell ended his paper with the following remark:

> *In conclusion, it should be emphasized that the present work ... is of the nature of a reconnaissance of new territory. It is to be hoped that the determinations made here by approximate methods will be replaced within a few years by others of much greater precision, based on accurate measures of the contours and intensities of as many lines as possible. An extensive field of work is open, and it is hoped that much more may be done at this Observatory.*

This statement is visionary enough to be repeated again, although I would replace the last three words with "in many places."

Finally, an ending side remark about the art of making and using model atmospheres. In the art museum in Pasadena, The Norton Simon Museum, a nice collection of art from many centuries is on display. Among the oil paintings there are several by Rembrandt Van Rijn. In the same room two particularly fascinating portraits face each other (Fig. 1.4). The first is from 1636–38, one of Rembrandt's many self portraits. Here the artist wears a characteristic beret, is about 30 years old but looks older and quite dignified—with a golden chain around his neck, a symbol of prestige. I fear that about 10 years ago we regarded model stellar atmospheres to be just as established.

The second portrait was painted about 10 years later, a portrait of a young boy, presumably Rembrandt's son Titus. It is a very charming picture of a vivid young person, a much more dynamic portrait, but unfinished. (In fact, it has been used in studies of Rembrandt's way of working.) It reminds me more of contemporary model atmospheres.

The user of model atmospheres, for example someone mainly interested in abundance

Fig. 1.4. *Left panel:* Self-portrait (c. 1636–40) by Rembrandt van Rijn at the Norton Simon Museum, Pasadena. *Right panel:* Portrait of a boy, presumed to be the artist's son Titus (c. 1645–50) by Rembrandt van Rijn, Norton Simon Museum, Pasadena.

analysis, may feel that such aesthetic aspects are less significant. Rightly so! But just as real children are dynamic, so are real stars. Careful scientific work often means preferring the unfinished attempt to catch reality over detailed static academic modeling, so far from the real world.

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