CONCLUDING SUGGESTIONS FOR FUTURE HIGH S/N SPECTROSCOPIC WORK ON STARS

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ABSTRACT. A summary of the main subjects discussed at this symposium is given, and some suggestions for future high signal-to-noise spectroscopic work, which could have a major impact on our understanding of the physics of stars and on astrophysics in general are presented.

1. INTRODUCTION

Let me begin this concluding talk with a few remarks on the interpretation of the term *very high S/N spectroscopy* that appears in the title of this symposium. I think it should be reserved to spectroscopy with a S/N of 300 or higher at resolutions R $\gtrsim$ 20,000. In many works presented at this meeting a S/N of 100 only has been reached, which in some cases was not sufficient to obtain unambiguous results. Another problem is that even if the S/N is very high the astrophysical results derived from high-resolution spectroscopy may be severely affected by *systematic errors* as emphasized in the paper by D. F. Gray. Examples are: unknown amounts of scattered light, uncertainties in the instrumental profile used in the reduction, non-linearity of the detector, and errors in the flat fielding. In order to determine the size of these systematic errors there is a need for a more careful comparison of spectra obtained with different instruments. Maybe one should set up a list of standard stars and standard spectral regions in order to be able to make such comparisons in an effective way.

2. INSTRUMENTATION

About one day of the symposium was spent on instrumentation for high S/N spectroscopy. It is evident from papers published and from the contributions at this symposium that three high-resolution instruments with RETICON detectors (the McDonald Spectrometer, the CFTH Coudé Spectrograph, and the ESO CAT/CES) have been the basis for the rapid development of stellar spectroscopy during the last 10 years. However, these instruments do not represent the final state of art. Several problems have been encountered and improvements could be made in the following respects:

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 613–620.

i) *Efficiency* of telescope, instrument and detector which according to the S/N obtained for a given stellar magnitude and exposure time is not higher than about 1%. One obvious way to improve the efficiency is to apply image slicers.

ii) *Spectral coverage* which is limited to a range of 50-100Å as determined by the length of the RETICON. With 2-dimensional CCD detectors it should be possible to cover larger spectral ranges. Furthermore, some spectrometers should be optimized for observations in the near UV, 3000 - 4000Å. This spectral region is very important for the study of early-type stars and very metal-poor stars, and some interesting elements like beryllium have spectral lines suitable for abundance determinations only in this spectral region (see paper by K. G. Budge et al.).

iii) *Flat fielding* which is not always as accurate as one would like due to different illumination of the optics by stars and flat-field lamps. In particular this is a great problem in connection with interference fringing in the near infrared for some CCD detectors. One possible solution is to feed the spectrometer through optical fibers.

iv) *Wavelength stability* that needs to be of the order of a few m/s in some research programs, e.g. the search for planets around stars or studies of stellar oscillations. Fiber optical scrambling may be one possible solution.

v) *Detectors* that should be made larger and more efficient especially in the near UV. An annoying problem is cosmic ray events, which produce disturbing spikes and limit the S/N severely for long exposures. Protection of instruments by heavy concrete should be investigated as a possible cure of the problem.

It is promising that many new high-resolution spectrometers have come into operation recently or are being built. Some of the improvements suggested above have already been incorporated. Thus S. S. Vogt reported on the Lick Observatory Echelle Spectrometer that seems to reach an overall efficiency as high as 4%. J. S. Yang gave new ideas for improving the efficiency, and H. Mandel as well as P. Felenbok and J. Guerin reported on fiber linked spectrometers.

A particular rapid instrumental development is taking place in the field of high-resolution infrared spectroscopy. S. T. Ridgway and K. Hinkle discussed new infrared detectors, which will make it possible to reach nearly as faint magnitudes in the infrared as in the visual spectral region. Fourier Transform Spectrometers remain an interesting alternative both in the visual and the infrared for the very highest resolutions or in cases where a very clean instrumental profile is needed.

In the future it is to be expected that the instrumental development will be very much influenced by the construction of very large telescopes. One of the major reasons for building VLT's is the possibility to extend high-resolution, high S/N spectroscopy to interesting classes of stars that cannot be reached by present days telescopes. However, it should be realized that it is very difficult to construct spectrometers for the VLT's with the same efficiency as for smaller telescopes. Detectors and gratings have to be scaled up in proportion to the diameter of the telescope in order to maintain spectral coverage and efficiency at a given resolution. Thus, the VLT spectrometers become very bulky and expensive. For example, an amount of 25 million DM is foreseen for the construction of Coudéroom, beam combination and a high-resolution spectrometer for the ESO 16 m VLT. Clearly, it is a challenge for astronomers interested in high-resolution spectroscopy to ensure that this amount of money is spent in the best possible way.

3. PHYSICS OF STELLAR ATMOSPHERES

About two days of the symposium were spent on the structure and physics of stellar atmospheres. This is a field, where the impact of the new generation of high-resolution spectrometers has been particular strong. A wealth of innovative research has been carried out during the last few years and was presented or reviewed at this symposium. Let me just mention a few highlights. The works of D. Dravins and D. F. Gray on line profiles and bisectors have given completely new information on velocity fields and granulation of stellar atmospheres. Spectroscopy of lines formed high up in the stellar atmospheres has led to a much better understanding of chromospheres, coronas and circumstellar envelopes not the least for T Tauri stars (see papers by I. Appenzeller and G. Basri). The impressive work of D. Baade on line profile variations has given new insight into the atmospheric structure and velocity fields of early-type stars. Doppler imaging is now applied for most spectral types and gives fairly detailed information on the distribution of stellar spots. Very accurate measurements of line profiles have made it possible to determine both the magnetic field strength in active regions and the fraction of stellar surface covered by the fields (see e.g. S. H. Saar's paper).

These new results are not only important for a better understanding of stellar atmospheres, but they are also of fundamental importance in a wider context. Thus, we need better models of stellar atmospheres to derive accurate chemical abundances, and we need information on stellar parameters like rotation and magnetic field strength in order to study the details of stellar evolution.

4. CHEMICAL COMPOSITION OF STARS

The last two days of the symposium were spent on stellar abundances. This is a field with a long tradition but relatively slow progress in the sixties and the seventies. Conflicting results on the details of the abundance patterns in stars were published and the distrust to the results obtained was widely spread. This was clearly expressed by two solar physicists in a paper entitled *"Can astrophysical abundances be taken seriously?"* (Worrall and Wilson, 1972). They questioned the reality of abundance differences at a level of a factor of four for the following three reasons: i) Published equivalent widths often disagreed with more than 50%. ii) An unphysical parameter (the microturbulence) was introduced in order to eliminate the dependence of the derived abundances on line strength. iii) The derived abundances were based on the LTE assumption.

How is the situation today after a decade of further work on stellar abundances based on spectra obtained with the new generation of spectrometers? Concerning the first problem there is no doubt that great improvements

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have been achieved. Equivalent widths are now measured with an accuracy of ±3 mÅ for the range 10 < W < 50 mÅ. Comparison of several sets of independent observations in the paper by D. Duncan confirms this. Thus, equivalent width measurements are accurate enough to allow abundance determinations to an accuracy of ±0.05 dex, if no other error sources were present.

Concerning the next problem the situation has also been much improved. The hydrodynamical models of the solar atmosphere by Nordlund (1979) show that not only the shape but also the *strength* of spectral lines are affected by the velocity field. To a high degree of accuracy this effect can be described by a single parameter, the microturbulence, as shown in the work of Simmons and Blackwell (1982). Furthermore, in the case of weak lines , W < 30 mÅ, the derived abundance is practically independent of the value of the microturbulence parameter adopted. Modern abundance determinations are often based on such faint lines.

There is however one snag that makes the derived abundances more uncertain than ±0.05 dex for some stars. The method of Simmons and Blackwell can only be applied if oscillator strengths are known to an accuracy of a few percent. Very few lines have been measured to that level of accuracy and therefore oscillator strengths derived from the solar spectrum are often used. This works well if the lines are weak in the solar spectrum as shown in the paper by R. J. Rutten. However, weak lines in e.g. metal-poor stars are rather strong in the solar spectrum. Thus, the derived gf-values are affected by uncertainties in the solar microturbulence and in the model atmosphere used for the sun. Because of this problem the derived abundances for metal-poor stars and for stars with T_{eff} and g much different from the solar values are often more uncertain than ±0.05 dex. Clearly, there is a great need for improved experimental oscillator strengths as also stressed in the paper by M. C. E. Huber. Physicists doing such measurements should be supported and encouraged by astrophysicists to continue and extend their work.

In connection with the third problem raised by Worrall and Wilson - the assumption of LTE - severe uncertainties still exist. As discussed by B. Gustafsson and as shown by P. Magain the derived abundances in metal-poor stars show a significant trend with exitation potential if LTE is assumed. The effect may be as large as 0.2 to 0.4 dex. This means that the interesting trends of various abundance ratios as a function of [Fe/H] derived by many participants in this meeting may be a product of the assumption of LTE. Obviously, there is a great need for non-LTE computations of spectral lines and fortunately this is possible with present days computers. Important work is being done by groups in Kiel, Munich, Uppsala and in the United States (see papers by D. Gigas, U. Heber et al., B. Gustafsson, and R. C. Peterson). Hopefully, the situation concerning non-LTE effects will become more clear within the next few years, but progress is considerably hampered by the lack of atomic data - in particular collisional cross sections.

In addition to the non-LTE problems inadequate model atmospheres also lead to considerable errors in the abundances derived. As reported by B. Gustafsson the solar iron abundance derived from the hydrodynamical model of Nordlund (1984) is significantly lower than the value derived from traditional homogeneous models. This is a serious problem that should be further investigated.

We conclude that errors in stellar abundances at present are dominated by errors in atomic data, in the models, and in the computation of line spectra. These effects could be responsible for some of the derived trends of abundance ratios as a function of [Fe/H], which are very interesting for studies of nucleosynthesis and galactic chemical evolution (see papers by J. W. Truran as well as E. Vangioni-Flam and J. Audouze). On the other hand very reliable results may be obtained if one is working differentially such that the above mentioned errors cancel. A good example is the study of Li abundance differences among F and G stars in open clusters (Boesgaard and Tripicco, 1986).

5. STELLAR PARAMETERS

It is well known that errors in the stellar atmospheric parameters, T_{eff} and g, introduce rather large errors in the abundances derived. Also in connection with studies of stellar structure and evolution there is a great interest in accurate values of these two parameters. As reviewed by B. Gustafsson the accuracy in the determination of T_{eff} and g has been much improved during the last few years. As shown in the paper by Perrin et al. the profile of H_{α} can be used to determine T_{eff} values to an accuracy of ± 35 K for solar-type stars. From Balmer lines in O and B stars one can determine log g with errors less than ± 0.15 dex (see paper by U. Heber et al.), and for late-type stars the surface gravity may be determined from the wings of strong, pressure-broadened lines. The method was demonstrated at this symposium in papers by J. Drake and B. Edvardsson. For very high quality line profiles the accuracy may be as good as ± 0.05 dex in log g (Smith et al. 1986).

As emphasized by W. Däppen at this meeting and as discussed in details by Gough (1987), accurate values of T_{eff}, g and luminosity (to be determined when parallaxes from HIPPARCOS become available) are needed to make a fundamental new investigation of stellar interiors by measuring the frequencies of stellar oscillations. The first (still controversial) results for Procyon, αCen and ϵ Eridani were reported on by E. Fossat. More convincing detection of oscillations of Pollux and Aldebaran was shown by P. H. Smith and R. S. McMillan. Clearly, these very interesting attempts to measure stellar oscillations should be continued with improved techniques (see paper by S. Frandsen).

6. SOME SUGGESTIONS FOR HIGH S/N SPECTROSCOPIC OBSERVING PROGRAMS.

In this section I would like to give just a few specific suggestions for high S/N spectroscopic observations that could have a major impact on our knowledge of stellar physics and chemical abundances of stars. These examples are listed according to the S/N and resolution that are needed to obtain good results.

6.1. S/N≃500, R≃100,000

Work on stellar granulation and convection is of fundamental importance for a better modelling of stars. Until now the relevant observations of bisectors have been carried out only for the very brightest stars. Extension to fainter stars representing all spectral types and to Pop. II stars is extremely important. Probably a VLT is needed to reach the Pop. II stars.

Detection and measurement of frequencies of stellar oscillations is a similar demanding field of utmost importance. Improved techniques will be necessary and a VLT will probably be helpful.

6.2. S/N≃300, R≃100,000

This is the kind of S/N and resolution needed to get accurate information on stellar rotation, turbulence, activity and magnetic fields or isotopic abundances. Limiting magnitudes are V = 6-7 with present days telescopes and spectrometers, e.g. the ESO CAT/CES. With larger existing telescopes and spectrometers with improved efficiency one should be able to reach V = 9-10 and with a VLT one may reach V = 12-13.

An interesting problem to be solved is the influence of parameters like rotation and magnetic fields on the global structure and chemical composition of stars. There is growing evidence that stellar colours and the strength of weak spectral lines are influenced by variations in other parameters than T_{eff}, g and chemical composition. Apparent abundance variations has been found among the Hyades stars (Cayrel et al. 1985). Unevolved Hyades F-type stars deviate very significantly from ZAMS field stars in the Strömgren c_1 - (b-y) diagram (the so-called "Hyades anomaly", Strömgren et al. 1982). Some open clusters, e.g. NGC752 (Twarog 1983) and NGC3680 (Nissen 1987) have a bimodal turnoff in the CM diagram. Only through a detailed study of the rotation, turbulence, activity and magnetic fields we can hope to find out which effects are responsible for these anomalies.

The study of isotope ratios is another field, where it would be extremely important to continue and extend very high S/N spectroscopy. As reviewed by D. Lambert isotope ratios in late-type giants give information about late stages of stellar evolution, whereas isotope ratios in dwarf stars provide information on the chemical evolution of our galaxy. For the latest spectral types, M, N, and C stars, very complicated spectra consisting of molecular bands are observed. Only recently it has been possible to model the atmospheric structure of these stars, synthesize their spectra and determine abundances and isotope ratios (e.g. Lambert et al. 1986). Extension of this kind of work to a substantial number of open and globular cluster giants and Pop. II field dwarfs would be much interesting.

6.3. S/N≃200, R≃50,000

This is the typical S/N and resolution needed to determine accurate abundances of most elements. Present limiting magnitudes are V = 11-12 with 3-4 m telescopes. In the future it should be possible to reach V = 14-15 with a VLT.

One of the best examples of the impact of high S/N spectroscopy on astrophysics is coming from recent work on lithium abundances in F and G stars. The striking similarity of the Li/H ratio in Pop. II dwarfs found by Spite and Spite (1982) is of great interest for cosmology, and the discovery of the dip in Li-abundance around T_{eff} = 6600 K in Hyades stars by Boesgaard and Tripicco (1986) together with the smooth decrease of Li/H for

T_{eff} < 6000 K (Cayrel et al. 1984) provide very interesting information on the internal structure of dwarf stars. Still, the mechanism of Li destruction is not well understood and it is unclear whether the Pop. II Li-abundance or the 10 times higher young Pop. I Li-abundance represent the primordial Big-Bang abundance. Much work is required to solve these problems, especially on Li-abundances in open clusters and field stars with different ages, rotation, metal abundance and activity. Also, the apparent constancy of the Li-abundance in Pop. II stars should be carefully tested, and stars further away in our galaxy should be observed.

Interesting work has been done in recent years on the trends of different abundance ratios in F and G stars near the sun. In view of the importance of such information for nucleosynthesis theories and models of chemical evolution it is evident that these investigations should be continued. Of particular interest is the scatter and possible discontinuities in the trends. Even more important would it be to extend the trends to a large group of very metal-poor stars, [Fe/H] < -3.0. For this purpose a VLT may be needed.

6.4. S/N≃100, R≃20,000

With this rather low resolution, accurate information can still be obtained on the parameters T_{eff} and g as well as abundances of some elements e.g. C, N, and O in early-type stars and O, Fe in late-type stars. Present days limiting magnitudes with 3-4 m telescopes are V = 13-15. With a VLT V = 18 may be reached.

At this symposium impressive spectra of giants in globular clusters and of supergiants in the Magellanic Clouds were shown (see papers by M. Spite et al., V. V. Smith, and M. Bessell). These works should be continued and extended to fainter luminosity classes in order to obtain more reliable abundances.

CNO abundances in main sequence B-type stars can give new information on the formation and evolution of stellar associations and on chemical gradients in our galaxy. The comparison with the chemical composition of HII regions provides an important consistency check. So far such work has been performed for B-stars ranging in galactocentric distance from 6 to 16 kpc (Gehren et al. 1985). With a VLT the investigations could be extended to the Magellanic Clouds or other nearby dwarf galaxies. New information on the primordial helium abundance may be obtained as well as information concerning the early galaxy formation epochs in the Universe.

Super-metal-rich stars were not discussed very much at this meeting. Yet there is no doubt that stars with [Fe/H] > 0.3 do exist. A good example is μLeo with [Fe/H] ≃ 0.5 (Branch et al. 1978). It is likely that such stars exist in large numbers and with [Fe/H] up to 1.0 in the galactic bulge (Whitford and Rich 1983). Determination of abundances in a substantial number of such stars seen through Baade's window could provide information on a stage of chemical evolution that is completely unknown today. However, a VLT is needed because the K giants in Baade's window are as faint as V = 17-18.

Finally, let me just mention the late stages of stellar evolution, blue subdwarfs and white dwarfs. As shown in the papers by U. Heber and J. L. Greenstein much new information has been gained by means of the new

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generation of spectrographs. Undoubtly, this type of work will continue to be a good example of the importance of very high S/N spectroscopy at modest resolutions.

7. CONCLUSION

The progress in high resolution, high S/N spectroscopy has been remarkable during the last decade but, as we have seen, much work remains to be done. Instrumentation at existing telescopes can still be improved significantly and the VLT's will give new possibilities in a few years. Many interesting observing programs are possible to carry out; just a few examples have been mentioned here. However, as I have tried to emphasize, it is also very important to improve physical theories and models used to interpret the observations. Otherwise we will not learn very much or we will get the wrong information even if the S/N of the spectra is very high.

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