

The Chemical Composition of Normal Stellar Atmospheres

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One must recognize that the determination of the chemical compositions of stellar atmospheres is beset with a number of difficulties, which persist even after decades of progress in theoretical interpretation and technical improvements in observational and experimental capabilities. The difficulty is that we cannot gouge out a sample of a star and analyse it by conventional methods; we are restricted to spectroscopic data!

There are some important differences between the analysis of a stellar atmosphere and a spectrochemical analysis that must be stressed at the outset. A spectrochemical analysis involves the comparison of a sample and a standard whose spectra are produced under identical conditions of excitation. Since one proceeds by a null method, a determination of the actual quantitative relationship between the intensity of a line and the number of atoms acting to produce it is not required.

The astronomical problem is basically different in that one must extract from the observed data, not only the required abundances of the elements involved, but also essential parameters of the stellar atmosphere - since the appearance of any spectral lines depends intimately on the temperature and surface gravity of a star and how the temperature and density vary with depth.

The observational data consist of measurements of the position λ (wavelength) of the center of a line, the total amount of energy subtracted by the line from the continuous spectrum (equivalent width), and the shape or profile of the line. The problem is further complicated by the circumstance that the lines frequently overlap. This provides no difficulty for an abundant metal like iron which is represented in solar-type stars by hundreds of lines, but becomes a serious problem for the very weak lines of rare elements. In addition, we often have measurements of the spectral energy distribution which gives significant clues to the temperature of the star, particularly when it can be compared with predictions of modern theories of stellar atmospheres. In stars hotter than the sun, one can employ the shapes of the hydrogen lines in order to establish stellar surface gravities, provided that the temperature has been reasonably well established.

The analysis of a stellar atmosphere may be carried out at three levels of sophistication.

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- (1) In the conventional curve of growth procedure the equivalent width w of the line (actually $\log w/\lambda$) is plotted against some function of gfA , where A is the abundance, g is the statistical weight of the lower level, and f is the transition probability. It is assumed that the atmosphere can be represented by a single temperature and pressure. In the Milne-Eddington model, it is assumed that the ratio of line to continuous absorption coefficient is constant with depth in the star. In another, the SS model, it is assumed that the absorption lines are formed above the region that produces the continuous spectrum.
- (2) In the method of model atmospheres, one plots $\log w/\lambda$ against some function of gfA , but takes into account the stratification of the atmosphere, i.e. the variation of temperature, pressure and absorption coefficients with depth in the stellar atmosphere. One chooses a family of model atmospheres which are specified by (usually) a normal H/He and H/metal ratio, effective temperatures, and surface gravities. For each of these models, one predicts observable parameters, notably the energy distribution, the shapes or profiles of the hydrogen lines, and the intensity ratios of certain lines that are sensitive to excitation conditions, e.g. the ratios of certain SiIII and SiIV lines in high temperature stars. One then compares the predictions of the models with the observed quantities for the star in question and chooses the best fitting model or interpolates a model that best fits the observations.
- (3) If observational material of very high quality is available, one may employ a yet more elaborate method, namely the calculation of individual line profiles. The great advantage of this method is that it uses all available observational data, whereas if one uses only the equivalent width of a line he is ignoring all the information contained in its shape. A further advantage of this method, which we refer to as spectral synthesis, is that one can handle overlapping lines, i.e., blends. In fact the method has been developed precisely to cater to the situation in which the line of interest, e.g., a line of Ag or Pb is heavily blended with some other metallic line.

The disadvantages of the method are first, that observational material of very high quality is required. That is, one must have the true profile of the line freed from all instrumental effects. Material of such high spectral resolution is available at the present time only for the sun, although

for a few very bright stars, we are approaching resolution of the requisite quality. Specifically, a few stars have been observed at Mount Wilson with sufficient resolution to justify the procedure. The McMath solar telescope at Kitt Peak can be used on the very brightest stars with extremely high resolution and it will be possible to secure excellent data for a number of very interesting ones.

The second disadvantage is that large blocs of computing time are needed, and tedious plotting of successive approximations is needed, although it is hoped that a computing routine can be developed to handle this situation.

At the outset, one needs a good model atmosphere. Fortunately, for the sun adequate models are available at least for the parts of the solar atmosphere wherein most of the line profile is developed. Secondly, one must also make some assumption about large scale motions of the gases in the atmosphere, i.e. turbulence. Finally, it is necessary to adopt some hypothesis on the collisional line broadening mechanism. Most lines are collisional broadened by quadratic Stark effect or van der Waals interactions with hydrogen atoms. If the profiles of the lines are sufficiently accurately measured, the broadening coefficients can themselves be determined empirically. The only remaining parameter is the product gfA and since the statistical weight of the lower level is known, the accuracy of the abundance determination is limited by the accuracy of the f -value measurement.

Some applications of this method, which has been employed by John Ross to determine the abundance of Chromium in the sun is shown in figures 1-4. Figure 1 shows the representation of the CrI $\lambda 5247.574$ line (Multiplet no. 18 in the Revised Multiplet Table). This is a simple profile for which an excellent representation is possible. The computed points are indicated by the circles.

Figure 2 shows the steps in the representation of the line profile. From a conventional curve of growth analysis (i.e. a previous abundance study) one has a preliminary estimate of $\log gfA$. The line is too strong. The second trial gives a line that is too weak and by an interpolation procedure one obtains a final curve which gives a good representation of the line $\lambda 4708.019$ (mult. no. 186).

Figure 3 shows a chromium lines $\lambda 4544.621$ of multiplet (33) blended with an iron line and a titanium line. Note that it is necessary here to represent both the Fe and Ti lines by varying their $\log gfA$'s until the profiles fit. For all of these lines it is necessary to make slight adjustments in the

collisional damping parameters.

Figure 4 shows the synthesization of the CrI $\lambda 5328$ lines. Here several strong contributors are involved and a number of successive iterations are required to reproduce the observed profiles. The CrI line is flanked by strong blending lines of other elements.

It is of interest that the line intensities and profiles can be predicted so precisely, we have assumed throughout that these lines are formed under conditions of local thermodynamic equilibrium. Yet the shapes and even the central intensities are astonishingly accurately reproduced.

It must be emphasized that these procedures are worthwhile only for observations of high accuracy and lines of particular interest. Ross considered the chromium lines because a great effort has been made recently by several teams of workers to derive f -values for lines of this metal. We mention the studies by Wilkerson and Charatis (Univ. of Maryland), by G. W. Wares and his co-workers at Air Force Cambridge, and most recently by Paul Byard at Ohio State University. Unfortunately, the precision of the chromium abundance derived by these procedures is disappointing in view of the effort involved. That is

$$\log N(\text{Cr})/N(\text{H}) + 12.00 = 4.73 \pm 0.26$$

where Corliss and Bozman's f -values have been used, whereas the f -values obtained by Wares et al. lead to a somewhat smaller abundance with a comparable scatter.

A limiting factor is and remains the uncertainty in the f -values for the lines we have to use in the abundance analysis. Different measurements continue to yield discordant results and until their problem is resolved, our efforts to determine abundances will be frustrated.

One method which aims to evade this difficulty is to compare the spectra of the program star with a standard star of presumably known composition. This method of differential curve of growth analysis has been employed by many workers since it was first used in the late thirties and early forties by groups at Harvard and elsewhere. The advantage of the method is that the poorly determined f -values cancel out while the effects of blends etc. tend to be compensated for, at least as long as one deals with stars of comparable spectral and luminosity types. Much valuable work has been done

by this procedure. For example, Wallerstein and his collaborators have analyzed many stars by comparing them with the sun. The method fails if the program and comparison stars differ by too large an interval in spectral type. For example, a comparison of the sun ($T = 5700^{\circ}\text{K}$) and Sirius ($T = 10,500^{\circ}\text{K}$) by this method is difficult because blends, the relative importance of arc and enhanced lines, etc. are so different in the two stars.

As methods of analysis are further refined and the quality of observational material improves, and particularly as good f -value determinations become available, we can expect a gradual improvement in abundance determinations. Unfortunately, the bottleneck is and will certainly remain the lack of adequate observational facilities. Many of those who are capable, able, and willing to work on abundance problems are unable to do so, simply because the necessary telescopic equipment does not exist.

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