Spectroscopic Study of a Sample of Visual Double Stars

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Basic Parameters of a Stellar Atmosphere

We learn what we know about stars from the photons that originate in their atmospheres and eventually reach our telescopes. Therefore, if we want to account for the spectral distribution of the radiation received from a star we must know the physical properties in its atmosphere. One of the great achievements of the last twenty years in the theory of the stellar atmospheres has been the calculation of detailed models of their average physical properties. This theory teaches us that the atmosphere of a well-behaved star can be characterized by a small number of parameters. Once they are specified, the computation of the model stellar atmosphere follows in a unique way, within the assumed approximations. The most important of these parameters are the effective temperature, the surface gravity and the chemical composition. For the sake of completeness, two more parameters have to be mentioned: the mixing length and the microturbulence. They pertain to very crude approximations behind which is hidden our poor understanding of such phenomena as convection or turbulence in the atmospheres of the stars. In general, the microturbulence and the mixing length are adjusted in a more or less empirical way. In fact, there are indications that they might not be fully independent from the other parameters.

The effective temperature, T_{eff}, is by definition the temperature of an ideal blackbody radiating the same total flux F as the star considered. If R is the radius of the star, its total luminosity is given by $L = 4\pi R^2 F = 4\pi R^2 \sigma T^4_{eff}$. The value of T_{eff} is typical of the temperatures found in the layers of the atmosphere where the continuum radiation is formed. The surface gravity of the star, g, is given by the relation $g = GM/R^2$ where M is the mass of the star and G is the universal gravitation constant. In hydrostatic equilibrium the pressure supports the weight of the atmospheric gas and, hence, is directly correlated to g. In principle the specification of the chemical composition of the atmospheric gas requires the knowledge of the individual abundances of about five to twenty elements that play a role in the determination of the state of the atmosphere and of its absorption coefficient. Fortunately, it turns out that the abundances of the important elements heavier than helium vary in lockstep, so that the specification of the chemical composition is reduced to two parameters: the abundance of helium and a general "metallicity" parameter, often referred to as [Fe/H], or [M/H]. There is however a restriction for the elements C, N and O which have recently been shown to follow a different pattern, in particular in giant stars, due to evolutionary effects.

The Determination of the Stellar Atmospheric Parameters

The direct determination of the effective temperature of a star requires the measurement of the angular radius of the star and the determination of the absolute flux received from it at the earth, integrated over the entire electromagnetic spectrum (ultraviolet + visible + infrared). For the determination of surface gravities, masses and absolute radii are needed. In some cases, the distance (i.e. the parallax) needs to be measured with good accuracy to convert angular diameters into absolute diameters.Thus, direct determinations of effective temperatures and gravities require measurements that are difficult and are feasible only for a restricted number of stars submitted to strong selection effects. For other stars, T_{eff} and g can be determined only by indirect methods which all make use of results derived from model stellar atmospheres.

The chemical composition cannot be measured independently of some temperature and pressure parameters. The strengths of the absorption lines in a stellar spectrum are the observable quantities which are the most sensitive to the chemical composition. However, they are also strongly dependent on the excitation and ionization conditions which prevail in the atmosphere and which are controlled by the values of T_{eff} and g. Thus, we have a highly coupled problem and we must derive a global solution from the analysis of the stellar spectrum.

Spectrophotometric and photometric techniques, which measure the distribution of the continuum radiation, as affected by the line blocking and by interstellar reddening, may provide good indicators for T_{eff}, g and [M/H]. They often lose sensitivity for the cooler stars where the coupling between the effects is harder to disentangle. A very detailed discussion of the problem and of its solution may be found in a paper by Grenon (1978, Publ. Observ. Genève, sér. b, fasc. 5).

Spectroscopic Methods

In any case the photometric metallicity indicators have to be calibrated upon results from high resolution spectroscopy of stellar line spectra. It is therefore important to have safe and accurate methods available for the analysis of stellar line spectra in view of the determination of the chemical composition. Since the effects of temperature, gravity and chemical composition on the line spectrum of a star are strongly coupled, it appears advisable, for the sake of internal consistency, to derive T_{eff} and g as well as the chemical composition from the analysis of the line spectrum itself.

The usual spectroscopic temperature indicator is provided by the relative strengths of lines of different excitations of a given ion of a given element. Interpreted with the help of the Boltzmann equation, they give an excitation temperature which is related to the effective temperature by means of a model stellar atmosphere. The relative numbers of atoms of a given element in the different possible states of ionization depend on the temperature and on the electron pressure, as expressed by the Saha equation. The "classical" spectroscopic method for the determination of g makes use of this property: the temperature being supposed known, an electronic pressure is chosen in such a way that the abundances deduced from the lines of two different ions of a given element are equal. However, the electronic pressure depends not only on g but also on the chemical composition in an intricate way. Usually the final solution is obtained at the end of an iterative procedure. Other spectroscopic indicators are sometimes used for the determination of the gravity. The strength of molecular lines depends on the dissociation equilibrium which is function of the pressure and of the abundances. Basically the method does not differ much from the ionization equilibrium. A third approach makes use of the fact that the broadening of the strong metal lines in the spectrum depends directly on the gas pressure (see Fig. 1). In this method, which requires observations of rather high resolution, the effects of pressure and chemical composition are more easily disentangled than in the previous ones. Its drawback resides in our insufficient understanding of the collisional broadening mechanisms at the atomic scale; it is compensated for by empirical fits to the solar spectrum, provided that the transition probability is known with sufficient accuracy.

The Arcturus Disillusion

Arcturus is a star that is very friendly to the astronomers. Since it is very beautiful and very bright, it has been measured many times and in very great detail. It has the best measured parallax for a giant star and several measurements of its diameter have been published. The high resolution Atlas of the optical spectrum of Arcturus published in 1968 by Griffin has been a landmark in the history of stellar spectroscopy. Several authors have used this Atlas for a detailed spectroscopic analysis. But, disappointingly, they obtain very discordant results. Estimates for its effective temperature range between 4,200 and 4,500 K. Even worse, the derived values for log g go from 0.9 to 2.1, i.e. g values differing by a factor of 16. With all the data available for Arcturus, a value of the mass can be derived from the values obtained for T_{eff} and log g. The resulting estimates of the mass given by the different authors vary between 0.2 and 1.2 $M_\odot$. Amazingly the iron abundances derived show little scatter, everybody agreeing on a value around [Fe/H] = -0.7 ± 0.2. The situation for Arcturus just exemplifies the general inadequacy and the lack of sensitivity of many of the standard spectroscopic techniques for the determination of T_{eff} and g. It has been so disturbing that it instigated the convention of a workshop in Cambridge in March 1981 where the problem was discussed in detail. The proceedings of this meeting are quite enlightening in that respect. (It is shown in particular how some basic inaccuracies in the measurement of the observable quantities translate into fundamental uncertainties in the basic parameters.)

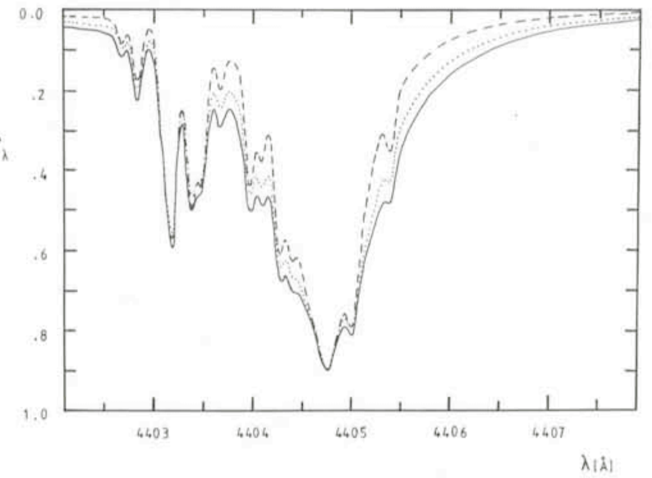

Fig. 1: *Relative flux (Γ_λ) of the synthetic spectrum with the Fe I 4404.8 Å line profile as computed for three different model atmospheres with a metallicity [Fe/H] = +0.15. The solid line corresponds to a model with T_{eff} = 5450 and log g = 4.5, the dotted line to T_{eff} = 5550, log g = 4.5 and the dashed line to T_{eff} = 5450, log g = 3.75. The profile is insensitive to the adopted microturbulence (ξ = 1.0 km/s). It has been further broadened by a Gaussian macroturbulence of 2 km/s, a rotation velocity v sin i = 2 km/s and a Gaussian instrumental profile of 2.5 km/s. The model atmospheres are very carefully scaled from the solar empirical model of Holweger and Müller (1974,* Solar Physics **39,** *19), with corrections interpolated in the theoretical grid of Bell et al. (1976,* Astronomy and Astrophysics, Suppl. **23,** *37). The blue wing includes contributions from blended atomic and molecular lines, whilst the far wing has been left on purpose free from blending.*

Visual Double Stars

The problem at stake is to try and find spectroscopic indicators that are more sensitive to the basic parameters of a stellar atmosphere than the usual standard techniques. The main difficulty is the highly coupled nature of the problem of the interpretation of the absorption lines. In such a case the best solution is to bring additional constraints into the problem in order to disentangle the effects of the different parameters on an observable feature. Such constraints may be found in the study of each component of a visual binary system. If their separation is wide enough, so that their individual magnitudes can be accurately measured, we know the ratio of their luminosities since they are located at the same distance from us. We can further assume that the two components have the same initial chemical composition. Binary systems are indeed usually thought to be coeval and, when their separation is so large that the tidal effects are negligible, the two components behave and evolve separately, just like single stars. These constraints are quite powerful and should prove extremely useful for a critical evaluation of the sensitivity of the different spectroscopic estimators to the variations of the different atmospheric parameters.

A sample of visual binary systems has been selected for that purpose. The systems were first chosen such that both components had spectral types going from late F to K. The brightest secondaries in systems of that kind have magnitudes fainter than 6 or 7. Since we want to make a systematic evaluation of the possible spectroscopic estimators of the stellar parameters, we must have as broad a wavelength coverage as possible with a resolution typical of most spectroscopic abundance studies. Until now, the ECHELEC spectrograph at the 1.5 m telescope has been the only one at ESO satisfying these observational requirements. The broad wavelength coverage is made possible by the use of the Echelle grating with the cross-disperser. Given the speed of the spectrograph, it was decided to select visual binaries with secondaries brighter than the 9th magnitude. The sample contains systems with pairs of unevolved stars as well as systems where one, or both, components are giant stars. A few systems are so near that they have good parallaxes and that it has been possible to determine their orbit. This will add further constraints on mass and luminosity, even though in some cases their angular separation is small and their individual magnitudes are less well measured. A number of pairs of this sample which are located in the northern hemisphere are observed from the Observatoire de Haute-Provence where a twin of the ESO instrumentation is available. Altogether spectra for 24 pairs have already been obtained. Other observations for these pairs will be secured in the next periods until 3 spectra are available for each component of each pair.

The stars of the sample will be submitted to a complete classical differential analysis. Unevolved stars will be analysed relative to the Sun and giants relative to ε Vir. Whenever the spectral types of the two components of a double star will not be too different, the secondary will also be analysed differentially relative to the primary. A search will be made for features (or ratios) most sensitive to a given parameter, but still sufficiently decoupled from the others. We intend to use the sample in a way similar to that used by Grenon (1978) for the calibration of the Geneva photometry for cool stars. For a given estimator, each binary pair provides a locus of variation at constant metallicity. Playing with the relative luminosities and stages of evolution of the components will allow to separate effects from T_{eff} and g. This method will first be used for components belonging to the interval of spectral types where classical spectroscopic analysis is generally considered to be valid (i.e. about F8 to K4). A few binaries in our sample have secondaries later than K5. It will then be interesting to see if, and how, some of our estimators can be extrapolated in their direction.

Finally, this study may yield several important by-products, such as detailed abundance differences between the components of a system containing a dwarf and a giant, or age determination and tests of evolutionary sequences in the HR diagram.

A number of our spectra have now been digitized and reduced, and we have begun the analysis for some of the "simple" cases, such as 16 Cyg A and B. We are specially investigating some interesting indicators. It seems that ratios formed with Fe I lines around λ4872, λ4889 and λ4891 would provide sensitive temperature indicators. Another example is the line of Fe I at λ4404.8 which seems much more sensitive to changes in gravity than in effective temperature, as illustrated in Fig. 1. Combined with another fainter Fe I line of about the same excitation, in order to cancel the effects of chemical composition, it should give a good gravity estimator.

This programme will be rewarding only if it is carried through with the greatest care. But we think the questions at stake certainly deserve the effort.

Quasar Surface Densities

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The story of the discovery of quasars has been told many times (see e.g. the 24th Liège International Astrophysical Colloquium 1983), nevertheless, it is always exciting to recall the first uncertain steps taken around 1960, when very little was known about this major component of the universe. In that period the identification of several radio sources, listed in the 3C catalogue, with more or less distant galaxies had been performed, but for many of them the optical counterpart was still unknown. In 1960 Matthews et al. (1) investigated with the 200" telescope of Mt. Palomar the fields corresponding to the sources 3C48, 3C196 and 3C286. They could not find any trace of galaxies, the radio position indicating on the contrary three objects of stellar appearance. At that time no radio star was actually known besides the Sun, thus the discovery raised some questions, which became even more puzzling when spectroscopic observations revealed that each of these "stars" emitted a lot of ultraviolet and blue light with a few emission lines, different from case to case, which could not be plausibly identified with any known element. Many theoretical possibilities were opened, but, before any thorough examination could be performed, the nature of the problem was completely changed with the identification of the radio source 3C273, carried out by Hazard, MacKey and Shimmins in 1962 (2) with the 210 ft Parkes radio telescope. By means of several lunar occultations, the position of the source was measured with an uncertainty less than 1" and its structure was shown to consist of two components separated by 19.5 arcsec. The relative accuracy of these measurements allowed an indisputable optical identification with a stellar object of about 13th V magnitude with an associated jet extending as far as 19.3 arcsec. Schmidt (3) took a spectrum of this object, which showed six broad emission lines which could be interpreted as being due to known elements assuming an unexpectedly large redshift of 0.158. It was possible to apply the same interpretation to 3C48, 3C196, and 3C286, when their spectra were reexamined, adopting respectively redshifts of 0.37, 0.87 and 0.85. At that time the radio galaxy 3C295 ($z = 0.46$) was already known, nevertheless the discovery was upsetting: if the redshift of 3C273 is cosmological, then its absolute magnitude is −27 (assuming a Hubble constant of 50 km/s/Mpc), that is about 40 times brighter than the brightest galaxies.

Since then many other amazing properties of these objects have been recognized: the ultraviolet excess, used as an aid for the identification of radio sources, led to the discovery of a few objects with similar colours far from any known radio source (the "interlopers" (4)), and finally a special survey for ultraviolet excess objects showed that radio quiet quasi stellar objects are not rare (5); variability, X-ray and gamma emission, the presence of absorption lines provided further information on the nature of these objects as well as new puzzling questions on the physical processes involved. The importance of complete surveys was soon felt, as stressed by Ryle and Sandage in the conclusion of their 1964 paper (at that time less than 10 QSOs were known): "The initial success of this survey suggests that many more objects of this type remain to be found. When a representative sample of these objects is available for study, such questions as the occurrence or non-occurrence of the objects in clusters of galaxies, the spatial distribution and the distribution over the plane of the sky, the presence or absence of light variations, the connection of the optical to the radio spectrum, the absolute luminosities and the dispersion about a mean, and the form of the redshift-apparent magnitude relation can be studied." Since then, in fact, a great effort has been made in order to establish complete samples of quasars down to fainter and fainter limiting magnitudes, up to higher and higher redshifts. In this subtle game astronomers have always had to face the presence of hidden selection effects, trying to disentangle the intrinsic properties of QSOs from instrumental biases. One of the most powerful tools available is the early-day UV excess method, which has now been refined in multicolour techniques.

A. Braccesi intended to take advantage of the quasar infrared excess and used an I plate, in addition to the same two-colour plate used in 1965 by Sandage and Véron, to construct a complete catalogue of candidates to a limiting magnitude of $B = 19.4$. The infrared excess was not entirely helpful at that stage due to the relatively large measurement errors; however the investigation was successful and led to the discovery of a number of new quasars (6), since most of the faint UV excess objects at high galactic latitude, as those selected in this survey, turn out to be quasars (of low redshift). This line of research was pursued and resulted in a sample of 175 UV excess objects down to $B = 19.4$ in the same field (7) and a sample of very faint ultraviolet objects down to $B = 20.1$ in a restricted 1.72 sq. deg. area of this field (8). These surveys constituted for many years the only ones with "sufficient size, completeness, and purity for proper analysis" (9) and are still, together with other samples selected by various authors (especially noteworthy is the survey of Schmidt and Green on 10,714 square degrees above galactic latitude 30° which is expected to be complete to $B = 16$), of extreme importance for the study of the change of the surface density of quasars with limiting magnitudes. Such observations are fundamental to