THE DETERMINATION OF STELLAR TURBULENCE BY LOW RESOLUTION TECHNIQUES

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INTRODUCTION

In this review the problem of measuring velocity field in stellar atmospheres from the observer's point of view is presented. Our purpose here is to discuss observational methods in which detailed analysis of line profiles is not necessary, i.e. methods based on measurements of total absorption of lines (curve of growth and narrow-band photometry), methods based on measurements of widths of lines (Goldberg-Unno method and curve of line width correlation) and measurements of differential line shifts. Therefore, our review will be limited to the discussion of basic assumptions of each method, to the analysis of their advantages and disadvantages, to a specification of a quantity which can be derived from a given method and finally to a brief presentation of the results. Usually, the low resolution methods provide an information about a particular component of the stellar velocity field. But the problem is more complicated as we do not know if particular components can be isolated from the stellar velocity field, thus, we do not know the real physical meaning of the measurable parameters. In this paper we shall adopt classical concept of micro- and macro-turbulence and convective type velocity. This simplified picture was criticized since 15 years on every colloquium devoted to hydrodynamic phenomena in the stellar atmospheres, but until now the theoreticians have not succeded in developing a theory which

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would satisfactorily interpret the observations.

Theoreticians would be satisfied if an observational method could be found allowing to distinguish between different types of oscillations and distributions of the sizes and velocities of turbulence. The reality is however more pedestrian, because the observables are averages over the angles and depth in whole stellar atmosphere. Therefore, even the most sophisticated theory of velocity field in stars can not be verified with observations unless it predicts some average parameters suitable for observations in the integrated light of stars. Even for the Sun, where observations of high resolution in space and time are available, the microturbulence derived from integrated light is not uniquely attributed to any local event, although, the theory of some local phenomena is quite satisfactory.

As already mentioned, our review paper is devoted to classical methods of observations. It does not mean that there is no progress in observational techniques (see the review of Gray), but it merely reflects the fact that the huge observational material accumulated over a half of a century is still open to theoretical interpretation.

THE CURVE OF GROWTH METHOD

The method of determination of the microturbulent velocity from the curve of growth is the most commonly used, though subjected to serious uncertainties. This method has been applied for determination of the ξ - parameter for about 700 stars in a wide range of T_e and M_v.

The microturbulence is determined by comparison of the observed COG (i.e. $\log(W/\lambda)$ versus $\log(gf\lambda) - \chi\Theta_{exc}$) with the theoretical one (i.e. $\log(W/\lambda)(c/v)$ versus $\log A$). The displacement of the empirical COG vertically and horizontally to fit the theoretical curve establishes c/v and N. Various types of theoretical curves of growth are available depending on the definition of log A: Wrubel's COG based on S-S and M-E approximations, Unsold's COG based on Minnaert's empirical line-profile formula, weighting function method and precise calculation of theoretical COG for a given stellar atmosphere model. It should be noticed however that the choice of the theoretical curve has a minor influence on the ξ determination. The last of the mentioned above methods is similar to the fine analysis with a one, but important difference. In the fine analysis theoretical and observational profiles are compared, while in the COG method the equivalent widths are calculated from the

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theoretical profiles and compared with the observational values of W. Profiles of weak and medium-strong lines can be determined only from high resolution spectrograms. They are subjected to instrumental and rotational broadening, both being unimportant for equivalent width determination. Thus, the most important advantage of the COG method lies in its applicability to fainter stars, for which high resolution spectrograms are not available.

The COG method assumes that the geometrical scale of turbulent elements is so small that the non-thermal velocity distribution can be convoluted with the thermal velocity distribution. The vertical shift of the observed COG relative to the theoretical one yields c/v, where $v = (v_{th}^2 + \xi^2)^{1/2}$. The assumption of Gaussian distribution of velocity of turbulent elements is of course a simplification which may not be fully justified.

In most investigations the microturbulence was derived as a by-product of the abundance analysis. Only few studies have been entirely devoted to the determination of the ξ, usually for narrow ranges of T_e and M_v (Chaffee, 1970; Andersen, 1973; Głębocki, 1972; Foy, 1976). These investigations are of great importance because of the homogenuity of the observational material. But a comparison of ξ derived for the same star by different authors usually displays a considerable discrepancies.

Statistical analysis of the behaviour of ξ on the HR diagram based on the published data has been made by different authors (for references see Gray, 1978). The results of these studies are very important for our understanding of the physics of velocity fields in stellar atmospheres. Unfortunately, these results should be regarded with caution. During the last twenty years not only the method of the COG evolved, as mentioned above, but what is more important the numerous new determinations of the oscillator strengths with increased accuracy, allow for investigation of second order effects in the COG method. These second order effects can noticeably change the derived values of microturbulence. There is even a believe that many uncertainties in the COG method preclude a coherent discussion of the distribution of microturbulence on the HR diagram when based on the data published by different authors. These uncertainties are well known and can be listed in the following order: errors in equivalent widths, errors in oscillator strength values, lack of data and/or correct formula for damping constant, magnetic intensification, hyperfine structure, non-LTE, errors in temperature and pressure gradients, non-gaussian distribution of turbulent velocity. The first two factors are the most responsible for the disagreement in the ξ determinations for the same star by different authors.

Errors in equivalent widths. The stellar curves of growth are based on spectrograms with dispersion from about 1.5 Å/mm to 30 Å/mm. The observers know that the accuracy of W determination in mÅ is of the order of the dispersion of spectrogram given in Å/mm. But, it should be kept in mind, that systematic errors in W are more essential than the internal accuracy of measurements. Wright (1966) and Smith (1973) compared several W scales. The accuracy of W determination is of the order of 5% for lines stronger than 100 mÅ, but may be as low as 50% for weak lines (25 mÅ). The tendency of equivalent widths to increase with decreasing resolution is a well known effect though its origin is not quite well understood. E.g. a comparison of W from 8.5 Å/mm and 2.7 Å/mm spectrograms showed that lower dispersion equivalent width scale is 30% larger than the higher, and is roughly independent of equivalent width (Smith, 1973). The equivalent widths determined from spectrograms of 16 Å/mm differ by a factor of two when compared to the data taken from 2 Å/mm spectrograms. A factor of two in equivalent width scale would mimic increase of microturbulence by about 3 km/s for γ Equ (Smith, 1973). The only way of reducing the errors in ξ due to systematic differences in W scale is to compare the equivalent widths of the program stars with those of the standard star, for which the W scale has been well established. Unfortunately only few observers take the spectra of their program stars together with a standard star in order to compare their W scale with that derived from the high dispersion spectrograms. Besides, there is still a lack of commonly accepted standard stars for equivalent widths calibration. Thus, it is often impossible evaluate the error of the individual ξ determination caused by uncertainty in W.

Uncertainties in oscillator strengths. In the last years the improvement in the determination of the oscillator strengths, especially for iron, has been significant. The number of neutral iron lines with very accurate gf values (0.1 dex, e.g. Blackwell and Shallis, 1979) has considerably increased. The situation is worse for other elements and especially for ions. The new scale of gf values differs from the old one not only by a constant factor but, what is essential by a factor including upper-level excitation potential. The new scale may change considerably the determination of microturbulence and explain the spurious dependence of ξ on excitation potential and height in the stellar atmosphere found by e.g. Bell (1951), Wright (1951), Warner (1964), Zeinalov (1970), Osmer (1972). For example the χ - dependent turbulent

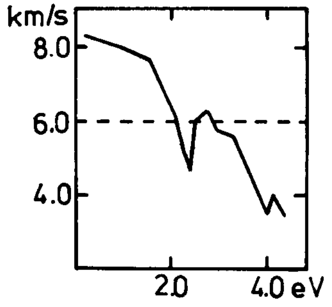

Fig. 1. Variation of the turbulent velocities with LEP derived by Zeinalov (1970) - full line, and constant velocity derived from revision by Hasegawa (1978) - dashed line.

velocity derived by Zeinalov (1970) for γ Cyg is caused by systematic errors in gf and W. Zeinalov used Corliss and Warner (1964) gf values. Hasegawa's reanalysis of that star demonstrated that adopting the new scale of gf χ- independent value of ξ is derived as shown in fig. 1 (Hasegawa, 1978). The investigation of Andersen (1973) demonstrated that ξ is reduced by about 30% for main sequence stars when using gf values of Garz and Kock (1969) instead that of Corliss and Warner (1964). For other stars this reduction of microturbulence may be even larger (Elste and Ionson, 1971). We think, that the well known discrepancies in ξ for the same stars analysed by different authors are in great extent due to differences in gf values. Almost every set of new gf determinations is applied to the solar curve of growth yielding a revised value of ξ . There is however a general lack of revision of microturbulence determination for standard stars (ϵVir, αPer, α CMi), what in principle unables the use of older ξ determinations for statistical investigation.

Uncertainties in the damping constant. The now available high accuracy of gf values especially for iron allows to investigate the influence of the second order effects (e.g. splitting of the COG due to collisional damping) which previously has been completely lost in the scatter of points in the COG. Some authors claim that value of damping constant is connected with the parity of multiplets. This effect has not been fully confirmed, but Foy (1972) found a splitting of the flat part of the solar COG. This splitting when translated into microturbulence is equivalent to 0.5 km/s. The approximations in the theoretical formulae for damping constant as well as poor experimental data make a detailed discussions of damping constant problem suspicious. The theoretical values of Γ are usually smaller than the observed ones. Many authors use an artificial enhancement factor in order to fit theoretical and observed profiles. The calculation by Smith (1973) showed that a change of Γ by a factor of 7.5 would mimic a change of ξ by 1.25 km/s. Similar results were obtained by Evans and Elste(1971) who showed that for the flat part of the COG the effect of an increased damping by a factor of 2 could be compensated by a decrease of micro-turbulence by an amount of 0.5 km/s. The influence of an error in Γ becomes negligible for lines near to the turn off point in the COG.

Magnetic intensification of lines. Spectral lines having rich Zeeman structure may increase their equivalent widths in the presence of strong magnetic field. The magnetic intensification is pronounced for medium-strong lines for which every π and σ component is saturated. For very strong lines collisional damping acts more effectively than Zeeman broadening. Zeeman intensification will rise the flat part of the COG analogously to the increase of microturbulence. Evans claims that 1 kGauss field mimics an increase of microturbulence of 1 km/s, and that this effect roughly scales (Smith, 1973), what is confirmed by the investigation of Hensberge and De Loore (1974). This conclusion is important when microturbulence of Ap stars is derived from horizontal part of the COG. The calculations of Havnes and Moe (1975) show that the Zeeman intensification is negligibly small (10% for 5000 Gauss) for equivalent widths near to the turn off point in the COG.

Hyperfine structure. Lines of some elements, like Co, Cu, Mn, Eu, are sensitive to their hyperfine structure. Curves of growth including HFS were calculated by Bely (1966) and Landi Degl'Innocenti (1975). Van Paradijs (1973) found that the intensification of Mn and Cu lines due to HFS mimics the value of microturbulence of 3.5 km/s in comparision to the adopted value of 1.2 km/s. Iron lines are insensitive to HFS intensification. The lines of Cu, Mn and some rare earths should be avoided in determination of ξ, especially in Ap and Am stars, where a joint effect of magnetic and HFS intensification may significantly change the derived value of microturbulence (Landi Degl'Innocenti,1975).

Non-LTE and uncertainties in models of stellar atmosphere. Non-LTE may be important for strong resonance lines in the early type stars. The profiles of these lines can be significantly changed when non-LTE procedure is applied, what translated to microturbulence can introduce corrections as high as 3 km/s (Mihalas, 1973). But for most faint and

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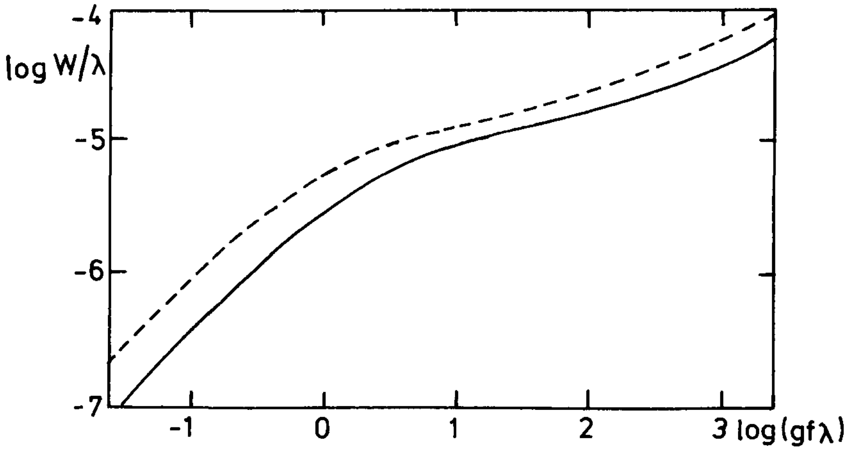

Fig. 2. Solar curves of growth with non-LTE - dashed line, and LTE - full line. Adopted from Dumont et al. (1975).

medium-strong lines used in the COG method the influence of non-LTE is negligible. Dumont et al. (1975) calculated the influence of non-LTE for a hypothetical 4-5 level atom plus continuum. Fig. 2 shows that the non-LTE calculations does not significantly change the COG. Application of non-LTE calculations for iron lines in Arcturus by Smith (1974) shows that the effect is on a level of detectability. Ignorance of non-LTE leads to an overestimate in ξ of 12%, i.e. 0.2 km/s.

Models of stellar atmospheres are still uncertain in that sense that they do not include the effects of stellar velocity fields. The heating by mechanical flux and blanketing effect can considerably change the temperature gradient in the uppermost layers of the atmosphere. The influence of a change in dT/dh on the slope of the COG was analysed by several authors. This influence can not be significant because weak and medium-strong lines used in the COG analysis originate in deeper photospheric layers. The results of Böhm-Vitense (1972) and Bonnell and Branch (1979) confirm the negligible effect of changes in dT/dh on the ξ determination from the COG, but it should be included in the abundance analysis. This conclusion is even more valid when microturbulence is determined from the lines near the turn off point in the COG.

The determination of ξ by the COG method is a valuable extension of the study of velocity field in the stellar atmospheres. No matter what is the real physical meaning of ξ we all agree that its quanti-

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tative change on HR diagram is important for our understanding of physical processes underlying the origin of turbulence and its connection with rotation, the depth of convective zone, mass losses and stellar winds. In this aspect the statistical investigations of the behaviour of ξ on HR diagram are essential. The COG method supplies most of the data for that kind of analysis. Unfortunately, as it follows from our review, the COG method is subjected to many uncertainties. Moreover, ξ is often derived as a by-product or fitting parameter, thus less methodological attention is paid to its determination. The following conclusions can be drawn from our discussion.

- Neutral iron lines should be used to the determination of ξ by the COG method. Iron lines are the most numerous in a wide range of effective temperatures. Their oscillator strengths have the greatest accuracy of 0.1 dex, also for faint lines.
- Spectrophotometric standard stars should be chosen in the whole range of T_e and M_v. These standards should have a very good determination of equivalent widths based on the highest resolution spectrograms and a carefully determined parameters of stellar atmospheres and velocity field. This would allow for a careful reanalysis of ξ for a huge number of stars.
- The microturbulence should be determined from the turn off point rather than from the flat part of the COG in order to avoid the influence of errors in damping constants, magnetic and HFS intensifications. These second order effects act effectively on strong and medium-strong lines rising the horizontal part of the COG. The high accuracy of gf values for faint lines permits now for a more precise evaluation of the turn off point with a partial elimination of personal factor which is also a source of discrepancies in the ξ determination by the COG method.
- Our experience shows that some discrepancies in ξ determinations for the same star by different authors can be removed if careful reanalysis is applied. The situation is worse for early type stars. The precision of oscillator strength for ions (Fe II, Cr II, Ti II) is still unsatisfactory for reliable determination of microturbulence.

Fast computer facilities supersede recently the COG method. Quasi-fine analysis like WIDTH program, where ξ is a fitting parameter are often used when analysing high dispersion spectrograms. However the above mentioned conclusions remain valid for this modification of the COG method.

NARROW-BAND PHOTOMETRY

The effect of line saturation in the COG can be utilized for detection of microturbulence by narrow-band photometry. Spectral regions with a bulk of lines from different parts of the COG can be found in stellar spectra. In the region where lines from the flat part are dominating blanketing effect is mainly a function of microturbulence, while in the region crowed with weak lines blanketing effect is sensitive to the metal abundance. In the standard narrow-band photometry systems colour indices are influenced by both factors. The sensitivity of colour indices on different atmospheric parameters was discussed by Gustafsson and Bell (1979) in their analysis of synthetic spectra. It turned out that some of the commonly used narrow-band indices like m_1, c_1, Uppsala systems, DDO systems are mildly dependent on ξ value. For illustration see figures in Gustafsson and Bell (1979). Analysis of the blanketing effect lead these authors to the suggestion that it is possible to invent a narrow-band photometric system suitable for the evaluation of microturbulence. For this purpose the following regions in the stellar spectra should be found: one with many weak lines and another with numerous medium-strong lines plus two reference regions free of any lines. The reference regions should not be too distant from their line regions. Index CI defined as

$$CI = 2.5 \log \frac{\text{flux of line region}}{\text{flux of reference region}}$$

would measure either metal abundance or microturbulence. Nissen and Gustafsson (1978) have proposed such a system based on measurements at the bands near to 4800 Å and 4980 Å for F type dwarfs. They observed 52 stars with $5800^\circ < T_e < 7200^\circ$ and $3.9 < \log g < 4.4$ and found that in this region of HR diagram, ξ is only weakly dependent on T_e changing from 1.2 km/s for $T_e \sim 5800^\circ$ to 1.9 km/s for $T_e \sim 7200^\circ$. Their result is in qualitative accordance with determinations by the COG method (Głębocki, 1973), see fig. 3. Systematic difference is caused by the adopted values of ξ for the Sun (Nissen and Gustafsson - 0.8 km/s, Głębocki - 1.3 km/s). Another narrow-band determination of ξ with the use of a very similar photometric system made by Gustafsson et al. (1974) for G8-K3 type giants. They observed 48 stars and concluded that microturbulence was constant for varying gravity and metal content. The mean value for this sample is equal to 1.7 ± 0.4 km/s. Their results confirm the conclusion of Głębocki (1973) based on analysis of the COG

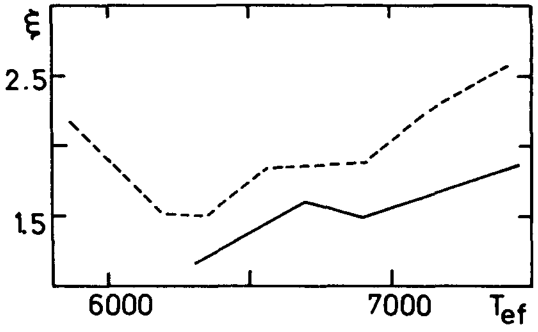

Fig. 3. Variation of microturbulence with T_e for F type dwarfs. Dashed line - narrow-band photometry data (Nissen and Gustafsson, 1978), full line - COG data (Głębocki, 1973).

data that the microturbulence is determined by the position of the star on HR diagram (see however Foy (1978) analysis indicating an age dependence of turbulence).

The narrow-band photometry method of ξ determination is based on the same unclear physical assumptions about the stellar turbulence as the COG method although it is methodologically quite different. It has an advantage of differential analysis avoiding errors in atomic data and errors in abundance of a particular element because of averaging the fluxes over the whole spectral region containing lines of different elements and different excitation potentials. Besides, photoelectric measurements of colour indices are more economical and accurate than the spectrophotometric determinations of absorptions of numerous lines. Troubles with establishing continuum in line crowded areas typical for spectrophotometric analysis are unessential in the narrow-band method. Besides, photoelectric measurements are much less time consuming especially in the elaboration of observations and they are more favourable in reaching fainter stars in comparison to high dispersion spectrophotometry.

There are however important drawbacks of the narrow-band photometry method. Its fundamental weakness lies in the calibration of the zero points. Even, when using sophisticated models of Bell and Gustafsson (1978) uncertainty in the calibration of zero point with real stars can be as large as about 1 km/s caused by errors in damping constant ($\pm$ 0.8 km/s), errors in the assumed value of ξ for the Sun ($\pm$0.3 km/s), errors in log g ($\pm$ 0.3 km/s) and because of non-LTE effects ($\pm$0.4 km/s) (Nissen and Gustafsson, 1978). These errors can change by an approximately constant value all the results for a given photometric system. Internal consistency of measurements is much better and a typical error does not exceed $\pm$ 0.15 km/s.

There are two obstacles which prevent a widespread use of narrow-band photometry for the determination of microturbulence in whole range of T_e and M_V. The most suitable photometric system for ξ determination consists of narrow spectral bands centered on regions with medium-strong lines, weak lines and reference regions free of lines. These regions can be established for stars in rather narrow ranges of tem-temperature and luminosity. For stars with considerably different T_e and M_V medium-strong lines can change into strong or weak lines and vice versa, and spectral regions free of lines may become overcrowded with lines. Therefore, the best narrow-band system should be established for rather narrow boxes on HR diagram. But in that case, for each box and each system good spectrophotometric standards with well known microturbulence parameter are necessary in order to establish the zero point of the ξ scale. It should be stressed once more that such standards are necessary for narrow-band photometry method, for COG method and for other methods as well.

A comparison of photoelectric narrow-band determinations of ξ with those from the COG method is shown in fig. 4. In this diagram the data are taken from different sources and because of the lack of standards

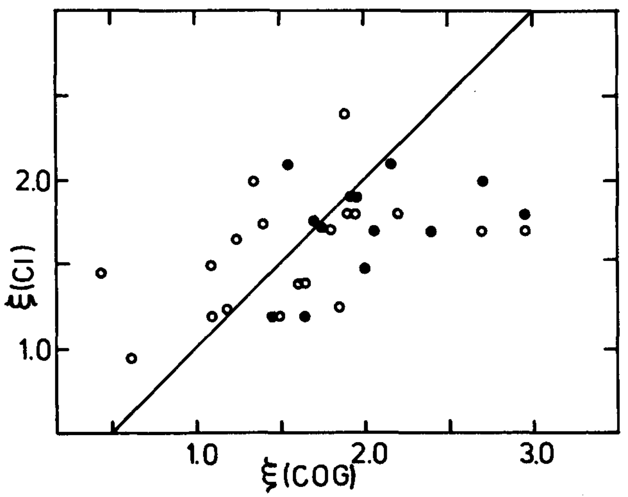

Fig. 4. Correlation between narrow-band and COG determinations of microturbulence. Circles denote stars with single COG determinations, points denote mean values from several determinations for the same star.

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they are not reduced to one system. In spite of the large scatter of points caused by errors in both methods the results are in rather satisfactory agreement. But, this figure explicitely reveals that any differences in microturbulence of the order of 0.5 km/s when found from inhomogeneous data can not be taken seriously.

GOLDBERG - UNNO METHOD

The method suggested by Goldberg (1958) and extensively applied to the solar lines by Unno (1959 a, b) rests on the comparison of two line profiles from the same multiplet to determine the Doppler width and hence ξ.

The basic assumptions are as follows:

a) the source functions of the two lines of the same multiplet are equal at the same geometrical depth;

b) the source functions do not depend on wavelength;

c) the profile is Gaussian, $\phi(\Delta\lambda) \sim \exp -(\Delta\lambda/\Delta\lambda_D)^2$;

d) the Doppler width, $\Delta\lambda_D$, is constant in the region of line core formation;

e) the continuous opacity is equal for the both lines.

When this assumptions are fulfilled line absorption coefficients are equal for the two lines at points of equal emergent intensity. This leads to a simple formula for the Doppler width

$$\Delta\lambda_D = \frac{0.4343\,(\Delta\lambda_A{}^2 - \Delta\lambda_B{}^2)}{\log(gf)_A - \log(gf)_B}$$

where $\Delta\lambda_A$ and $\Delta\lambda_B$ are widths of A and B lines at the same emergent intensity. In order to avoid errors connected with the pressure broadening, only the lines with Voigt parameter $a < 0.01$ should be used and measurements must be limited to $\Delta\lambda < \Delta\lambda_D$. Source functions of the both lines should be the same with the tolerance of only about 2%. In spite of these severe limitations it is not difficult to find at least few pairs of lines useful for the Goldberg-Unno method. The best results are obtained when the two lines are of comparable (but not equal) intensity, their lower excitation potentials are the same and they are not very distant ($\lesssim$ 50 Å) in the wavelength scale. The influence of errors in determination of the $\Delta\lambda$ is reduced when the measurements are made at the level of intensity equal to the center of the weaker

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line ($\Delta\lambda_A$=0). Unfortunately, because of the discussed above assumptions and restrictions the Goldberg-Unno method can be used only if the spectrograms with dispersion better than about 5 Å/mm are available.

Up to date nine stars were studied with the use of this method α CMi and α Boo (Sikorski, 1976) α Boo, ε Dra, δ Dra, ε Cyg, η Cep, γ Cep and τ Cep (Stenholm, 1977) and τ Uma (Zaremba, 1979). The resulting average ξ values for these stars are in good agreement with those derived from the COG method. An important advantage of the Goldberg-Unno method is the possibility of evaluating the changes of ξ with height in the stellar atmosphere. Using pairs of lines of different central depths, ξ values can be found for different emergent intensities, i.e. for different layers in the stellar atmosphere. The most serious problem is the estimation of a layer of formation of a given point in the line profile. How troublesome and misleading could be such a determination has been demonstrated by Athay (1972). The problem is even more complicated when the calculated contribution function differs considerably from the response function. Besides, the layer of formation of a given point in the profile extends sometimes up to 3/4 of the thickness of the photosphere. Therefore, the attribution of the ξ- value to a given depth in the atmosphere is subjected to serious errors. With all the caution given to these uncertainties, results for the Sun and the stars suggest an increase of microturbulence in the upper photospheric layers ($\log\tau_5 \lesssim -3$) and in some cases a slight increase in deep layers ($\log\tau_5 > -1$). The depth dependence of turbulence was studied in three K2 giants and the Sun using widths of weak lines formed in the wings of the H and K lines. Ayers (1977) found that non-thermal velocity component in the Sun is constant at 1.6 km/s between $\log\tau_5$=0 and -3, while Stencel (1977) found that the velocities increase outward in K2 giants and the higher the luminosity, the steeper the gradient.

It should be remembered that the Goldberg-Unno method can not be applied when broadening by convection, macroturbulence and rotation is not negligible. But for late type stars the results based on weak and medium-strong lines are undoubtedly reliable. In spite of the discussed above limitations the Goldberg-Unno method should be recommended mainly because of its simplicity in practical application.

THE CURVE OF LINE-WIDTH CORRELATION METHOD

In order to utilize measurements of the line shapes for the studies

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of stellar turbulence a method called curve of line-width correlation (COLWC) was proposed by Huang and Struve a quarter of century ago. It is well known that microturbulence causes only broadening of line without changing its total absorption. If the velocity field in the stellar atmosphere is assumed to be depth-independent and can be represented by one value of microturbulence and one value of macroturbulence, then a unique relation log W versus log $D_{1/2}$ should exist, where $D_{1/2}$ is the half width. This relation is called curve of line-width correlation. Theoretical COLWC has been calculated by different authors for given model of stellar atmosphere with parameter b defined as the ratio of macro- to micro-turbulent velocity, $b = v_{macro}/\xi$. In order to establish ξ and v_{macro} for a given star the theoretical curves are slid both vertically and horizontally until a curve for a particular b gives the best possible fit to the observations. Because of the difficulties with the unique fit usually, the microturbulent velocity is independently derived from the COG method, while the obtained value of b permits to derive the macroturbulent velocity.

The COLWC method though simple in principle is burdened with serious drawbacks. The scatter of observational points is usually too

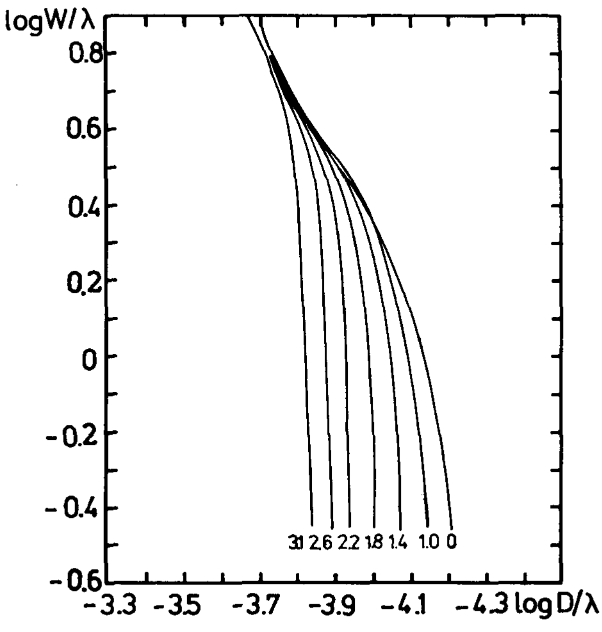

Fig. 5. Theoretical curves of line-width correlation for different ratios of macro- to micro-turbulence velocities.

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large for a unique determination of the b parameter. Some improvement of the procedure is possible when mean values rather than individual observational points are plotted on diagram (Bell and Rodgers, 1964, 1965). But even then the observations can not be usually fitted by a single curve. That is why the COLWC method has not been widely applied. The macroturbulence has been derived by this method only for α Cyg, δ CMa and the Sun (van den Heuvely, 1963), β Dor (Bell and Rodgers, 1964), δ CMa (Bell and Rodgers, 1965) and α CMi (Evans et al., 1975). Some modifications were introduced to the COLWC method by Evans et al. (1975). They measured widths of lines at 1/2 and 3/4 of central line depth and constructed plots of log W versus $\log(D_{3/4}/D_{1/2})$. This modification did not however removed the disadvantages of the classical COLWC. The modified COLWC was tried unsuccessfully in an analysis of early type stars by Slettebak (1956).

From the practical point of view the developments of this method seem to be purposeless. Only high resolution spectrograms could reduce errors in the measurements of line-widths and diminish the scatter of points on the COLWC diagrams. But for high dispersion spectra fine and/or Fourier analysis provide much more reliable evaluation of the parameters describing the velocity fields in the stellar atmospheres.

DIFFERENTIAL LINE SHIFTS METHOD

Differential shifts of stellar lines can occur when the convective type velocity field in a stellar atmosphere is coupled with the differences in the depth of line formation. If the stellar disc is covered by small convective type cells, similar to solar granulation, then a relation between differential shifts of lines, $\lambda^{*} - \lambda_{lab}$, and their low excitation potentials, χ, should be expected. High-excitation spectral lines are preferentially formed in the hot, rising and thus blueshifted elements, while low-excitation lines are preferentially formed in the cooler sinking and redshifted elements. In the solar atmosphere a correlation between continuum brightness and upward velocity is most pronounced for weak lines formed in the deeper layers and decreases for lines in the higher layers (Canfield and Mehltretter, 1973). Thus a correlation between differential line shifts and the strength of lines should be expected. This effect known as Burn's effect has been observationally confirmed by Głębocki and Stawikowski (1969, 1971) and Beckers and Nelson (1978). The relation between line shifts and low exci-

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tation potential (VR-LEP) have been found by Lambert and Mallia (1968) and Głębocki and Stawikowski (1969, 1971).

The measurements of differential line shifts require very high dispersion spectrograms. It is possible to measure stellar line positions in high quality spectrograms with an accuracy of 2 microns what for a dispersion of 2 Å/mm corresponds to 0.1 km/s. Because of uncertainties in laboratory wavelengths, measurements of stellar line shifts should be made either relative to very accurate low-pressure laboratory wavelengths or relative to the Sun, whose wavelengths are known with an accuracy of 1 mÅ or better. Otherwise pressure shifts or errors in laboratory λ scales may introduce spurious effects (Głębocki and Stawikowski, 1971). The differential line shifts are expressed in velocity units, VR = $(\Delta\lambda/\lambda)c$. The solar line shifts change their sign at the limb. This might be important when differential shifts are analysed in stars, where integrated light is observed. The contribution of the limb to the integrated light is however small, especially when limb darkening is taken into account.

The results of the differential line shifts measurements are usually presented by the gradient in the VR-LEP relation $A = \Delta VR/\Delta\chi$. Fig. 6 shows the VR-LEP relation for α Boo obtained by Dravins (1974). The points represent individual shifts for neutral metal lines derived from Griffin's spectrograms of 1.5 Å/mm (Griffin and Griffin, 1973). The gradient A amounts -0.45 km/s/eV. Stawikowski (1976) obtained the A

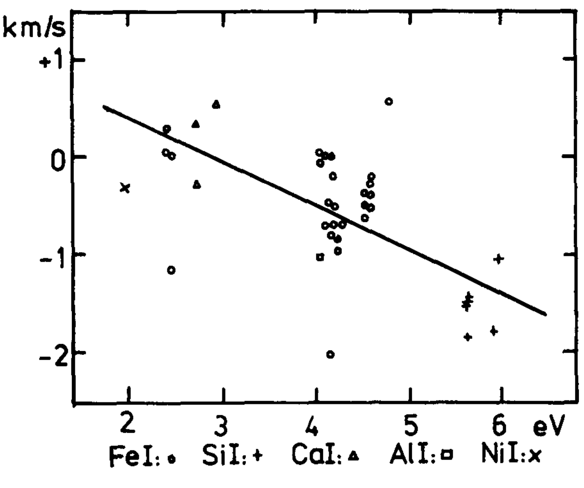

Fig. 6. VR-LEP relation for α Boo according to Dravins (1974). Symbols represent measurements of individual line shifts.

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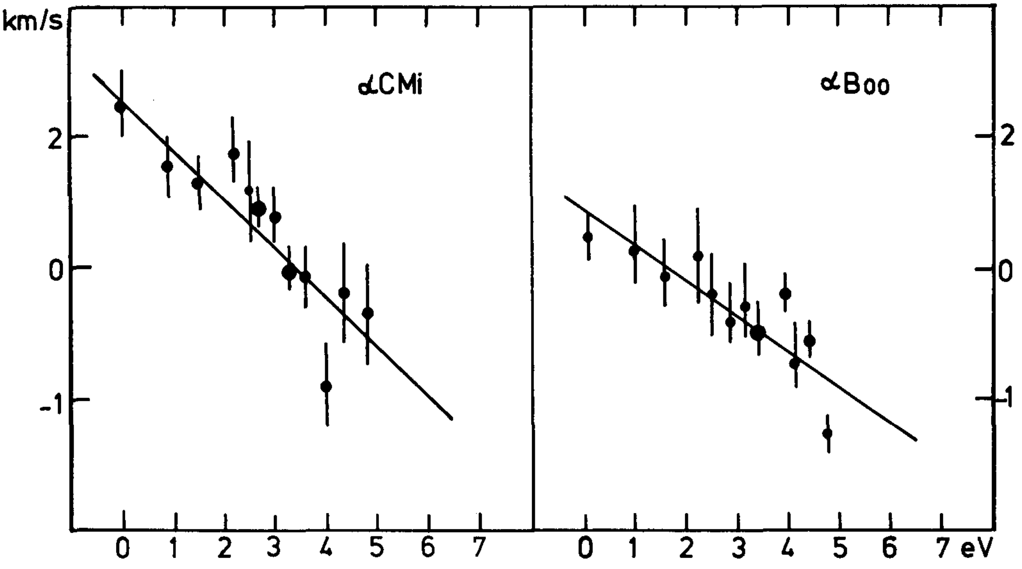

Fig. 7. VR-LEP relations according to Stawikowski (1976). Each point represents mean value of line shifts for several dozens of Fe I lines. Gradients (full lines) has been fitted to the points by the least square method.

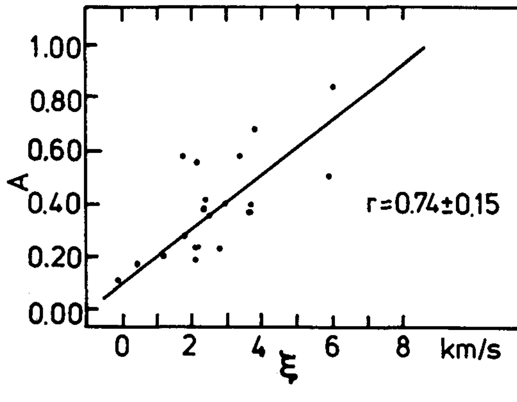

Fig. 8. Correlation between the value of gradient A and COG microturbulent velocities. Correlation coefficient amounts 0.74.

values for 20 F, G and K type stars. His results were based on inhomogeneous observational material with the dispersion of 2 to 8 Å/mm. Examples of VR-LEP relation are shown in fig. 7. Each point on these

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diagrams represents an arithmetic mean of several doznes VR measurements for lines with a given value of χ. A correlation between the A values and microturbulence is shown in fig. 8.

The VR-LEP method suffers from two serious shortcomings. First, it requires very high dispersion spectrograms; second and the essential, the results of line shifts when presented as a gradient A can not be explicitely converted to the convective type velocity in the stellar atmosphere. Even when a simple two-column model of atmosphere is adopted with a very crude mathematical treatment, the observed slope in the VR-LEP relation depends not only on convective velocity, but on the mean excitation temperature, on the temperature difference $\Delta T = T_{hot} - T_{cold}$ and on the percentage of disc area covered by the hot columns, S. Even for the Sun these quantities are poorly known. For stars ΔT and S have to be treated as free parameters in a function relating the observed gradient A with the convective velocity.

Schatzman and Magnan (1975) presented a slightly different interpretation of the observed VR-LEP relation. They assumed that the velocity of the ascending and descending convective bubbles can be represented by a Gaussian distribution. Additionally, they made an assumption that a unique relation exists between the temperature of the bubble and its velocity. Owing to the differences in lower level populations between hot and cold bubbles coupled with the upward and downward velocities a theoretical relation between differential shifts and lower excitation potential and the line strength has been derived. However, the number of free parameters in this approach has not been reduced in comparison with the column model. The authors stressed that the principal weakness of their interpretation lies in the ignorance of the correlation length of the turbulence. They have considered only the microturbulent situation, i.e. the mean free path of the photon being smaller than the size of convective element. The opposite situation corresponds to the theory of column model.

In spite of the difficulties with the interpretation of VR-LEP relation this method is a valuable complement of the stellar velocity field studies. It presents the interesting possibility of separating stellar turbulence into its physical components by comparing differential line shift results with other measurements of turbulence in the same star.

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