PROBLEMS AND PROSPECTS OF MULTICOLOR STELLAR PHOTOMETRY

V. Straižys

Vilnius Astronomical Observatory

Intermediate band multicolor photometry now is one of the principal methods to obtain information on stellar temperatures, luminosities, metallicities, peculiarities and interstellar reddenings. The method has some advantages over the method of stellar classification by visual inspection of low dispersion spectral images:

1. Multicolor photometry permits us to reach much fainter stars than the objective prism spectral method if we compare both methods at the same level of accuracy.
2. The photometric method gives quantitative values of stellar parameters (quantification) instead of only qualitative estimates of temperature, luminosity or metallicity from spectral plates (classification).
3. Photometry gives, in parallel with stellar quantification, another very important parameter - interstellar reddening which is practically impossible to determine from photographic spectra.
4. It is much easier to join multicolor photometry with an automatic classification system. Practically it is possible to observe with a photoelectric photometer on line with a computer and to see the position of every star measured on the HR diagram.
5. Multicolor photometry can be used in crowded regions of the Milky Way, in clusters and other galaxies, where it is impossible to obtain objective prism spectra without overlapping.
6. For the spectral classification of stars in two or three dimensions very good telescope optics and constant seeing conditions are necessary while multicolor photoelectric measures of stars can be made with inferior optics

and even in conditions of changing transparency and cirrus clouds if simultaneous photon counting in all spectral bands is realized.

Up to now a number of intermediate band systems have been proposed. All of them attempt to classify stars in some dimensions, however most of them operate in limited ranges of temperatures, luminosities, populations or reddenings. The most serious obstacle for most of the systems is the presence of interstellar reddening. Consequently most of the systems cannot avoid the necessity of some information from stellar spectra. This limits the use of most multicolor systems for the classification of stars fainter than 13^m for which there is no spectral classification from objective prism spectra.

Fortunately, it is possible to solve the classification problem of reddened stars by pure multicolor photometry. As far as I know the only intermediate band photometric system which does not need the assistance of objective prism classificiations is the Vilnius system which has been in use at least ten years. It was described most recently in my monograph Multicolor Stellar Photometry in Russian, Straižys (1977) and in English, Straižys (1973) and Straižys and Sviderskienė (1972). This system consists of seven magnitudes at 3450, 3750, 4050, 4660, 5160, 5440 and 6560 Å with half widths of the order of 200 Å. It is possible to classify any collection of stars, including samples of different temperatures, luminosities, populations, interstellar reddenings and some kinds of peculiarities. All seven magnitudes are not always necessary. If some information from objective prism spectra is available the number of magnitudes for classification or quantification of stars diminishes. Usually five magnitudes are sufficient for three-dimensional classification and interstellar reddening determination if rough spectral types are available. However, the system is destined for classification of stars having no additional information from stellar spectra. In this case seven or six magnitudes are usually essential.

For the quantification of stars in spectral classes and absolute magnitudes or in temperature and gravities three methods were suggested in our earlier publications. The first method is based on traditional Q, Q diagrams claibrated in two dimensions (Straižys and Sviderskienė 1972). Another method uses reddening-free energy distribution curves Q, λ (Straižys 1974). The third method described in the monograph Multicolor Stellar Photometry and in my communication in IAU Symp. No. 80 in Washington (Straižys 1978) uses five independent reddening-free quantities Q calibration in spectral classes and M_V or in temperatures and log g. From seven magnitudes we can form six independent color indices and from six indices we can form five independent parameters Q. If we use as a dereddening index Y-V, then the parameters Q are calculated by the equation

$$Q_{mYV} = m-Y - \frac{E_{m-Y}}{E_{Y-V}} (Y-V).$$

The first method, which uses Q, Q diagrams, is the simplest to apply but it does not use all the information which is obtained by measuring the star in seven colors. The second (Q, λ method) uses all the information but it is difficult to apply when one classifies the star in two dimensions by shifting the curves Q, λ. The third method uses all the information available and it is very simple in applying both graphically and with computer. Let me explain the main idea of this method.

At the beginning the parameters Q_{mYV} are calibrated in temperatures and gravities. For this stellar model atmospheres or real stars with known T_{eff} and log g can be used. So we obtain five plots with Q_{mYV} on the ordinate, θ_{eff} on the abscissa and log g = const isolines. These five plots of type Q, θ_{eff} are then transformed for a measured star into a diagram of log g, θ_{eff} with different curves for different Q. If the star under investigation has no peculiarities and if all Q are calibrated in log g and θ_{eff} without errors, then we should expect that all five curves, log g, θ_{eff} corresponding to different Q_{mYV} will intersect at one point corresponding the the values log f and θ_{eff} of the star (Fig. 1). Due to observational errors in Q the curves can intersect not in one point but in some area whose dimensions will increase with the diminishing accuracy of the observations. We can expect also that lines of log g, will intersect at different points for the stars having peculiarities in their spectra (Ap, Am-type stars, subdwarfs, white dwarfs, etc.).

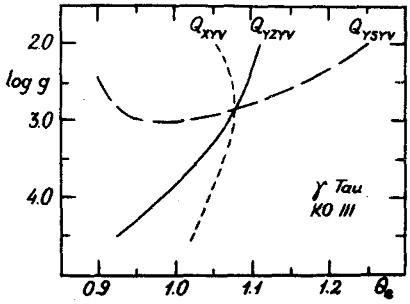

Fig. 1. Q isolines in the log g, θ_{eff} plane for the star γ Tau

The wrong calibration of parameters Q in temperatures and gravities will cause the same effect: the lines corresponding to different Q will not intersect near one point. Therefore the exact calibration of the Q parameters is of the highest importance.

At the beginning we tried to calibrate the parameters Q in temperatures and gravities using model stellar atmospheres as most other authors do. This method of calibration is the simplest and the most direct. However, the accuracy of calibration depends on the correspondence of model energy distribution curves to real stars. The model energy curves most suitable for calibration were computed by Kurucz (1978) for the stars from O to early G and by Peytremann (1974a, b) for the stars from A to early G. Computed color-indices for Kurucz models of B-type stars show satisfactory agreement with color indices of real stars of different luminosities and these models can be used for calibration. However, the ultraviolet Kurucz model indices begin to deviate from the stars starting with early A-type stars in the sense that model energy curves in ultraviolet are too strong. Peytremann models are good for A and F-type main sequence stars but begin to deviate for G-type stars in the same direction as Kurucz models. At the same time Peytremann model color indices of supergiants show very bad agreement with real stars. In this respect the Kurucz models are much better. To summarize, the best model atmosphere energy curves, including line blanketing, do not represent real stars in a sufficiently wide range of temperature and gravity and therefore it is dangerous to use them to calibrate photometric systems including ultraviolet and violet magnitudes.

It would be best to calibrate the system using certain real stars for which temperatures and gravities are known from spectrophotometric investigations. Unfortunately, up to now such a set of stars does not exist. The accuracy of determinations of temperatures and especially of gravities is still very unsufficient and serious differences between different authors both of systematic and accidental character exist. As a result we cannot yet use individual stars for calibration purposes.

It is possible, however, to diminish accidental errors by averaging θ_{eff} and log g values for groups of stars having the same MK spectral type. If we determine mean color indices and compute mean Q values for the same MK types we can interconnect Q values with T_{eff} and log g. The quantities Q suitable for quantification of stars in different temperature ranges were calibrated in such a way. They were used to quantify some hundreds of stars observed in the Vilnius photometric system. The quantification was made by a computer on the base of formulas expressing log g = constant isolines in the Q, θ_{eff} plane. These formulas were used to compute curves in log g, θ_{eff} plane for a given value of Q determined from the observations. The mean point of area encircled by intersecting lines corresponding to a different Q was considered as an optimum position of the star in the log g, θ_{eff} diagram.

We have used for the quantification of stars the calibration in θ_{eff} and log g determined only from spectroscopic determinations. The calibration from model stellar atmospheres was not taken into account because it gives wrong results, especially for the stars of higher luminosity. In Fig. 2 it is shown how different calibration isolines are obtained on the diagram Q_{UPY}, Q_{XYV} for the quantification of A and F-type stars. The left diagram is calibrated by spectroscopic data and the right one by Kurucz model atmospheres.

We have determined θ_{eff} and log g values for the A-F-type stars common between the Vilnius observatory system and the uvby system. The correlation between log g values determined from Vilnius photometry and by Philip et al. (1976) from the diagram c_1, b-y, is shown in Fig. 3. The correlation of both determinations is not very good and shows scattering with mean square dispersion $\sigma = \pm 0.15$. Additionally, a systematic effect is seen. Determinations in the uvby system give the values of log g considerably too large in comparison with our results for the stars of higher luminosity. The cause is the different calibration of the diagram c_1, b-y by model atmospheres.

It is important to intercompare both systems more directly without the influence of calibration effects. The c_1, b-y diagram has its analog diagram (U-X)-(X-Y) versus Y-V in the Vilnius system. The deviation of points of A-F type stars from ZAMS on these diagrams is a measure of gravity. So we can compare the deviations δc_1 and $\delta[(U-X)-(X-Y)]$at b-y or Y-V=constant. The dependences of both δ are shown in Fig. 4 for different intervals of temperatures. The mean square dispersion is of the order of ± 0.03 what corresponds to mean square dispersion of log g ± 0.11. This dispersion is somewhat less than that determined earlier from diagrams with different calibrations.

It is obvious that photometric quantities should be calibrated in log g, not in M_V. On the other hand absolute magnitudes are necessary to determine the distances of the stars. So, it is very desirable when possible to change the calibration in log g into a calibration in M_V. The most proper solution would be the calculation of M_V from log g but for this we should know stellar masses but usually these are unknown.

Trying to determine M_V we calibrated all our parameters Q in spectral types and absolute magnitudes instead of temperature and

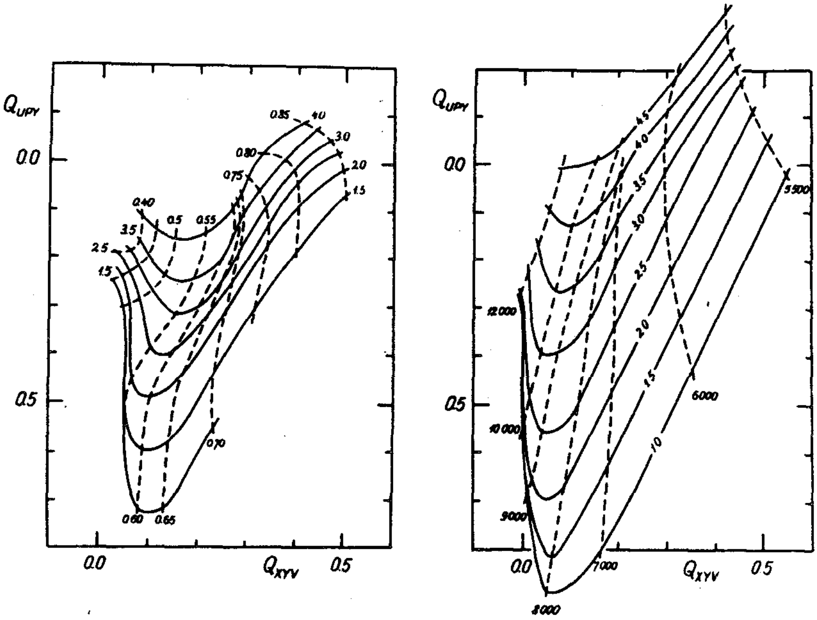

Fig. 2. Q_{UPY}, Q_{XYV} Diagram calibrated in T_{eff} (or θ_{eff}) and log g using the theoretical parameters determined spectroscopically (left) and from Kurucz model atmospheres (right).

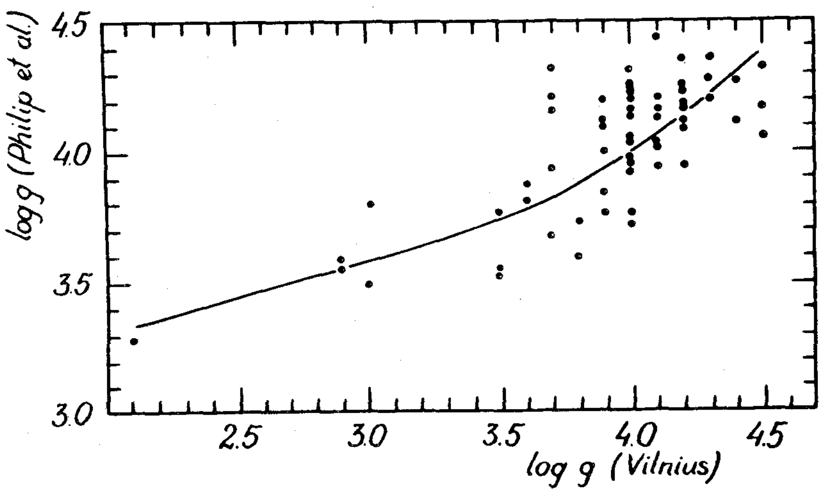

Fig. 3. Correlation between log g determined from Vilnius photometry and by Philip et al. (1976).

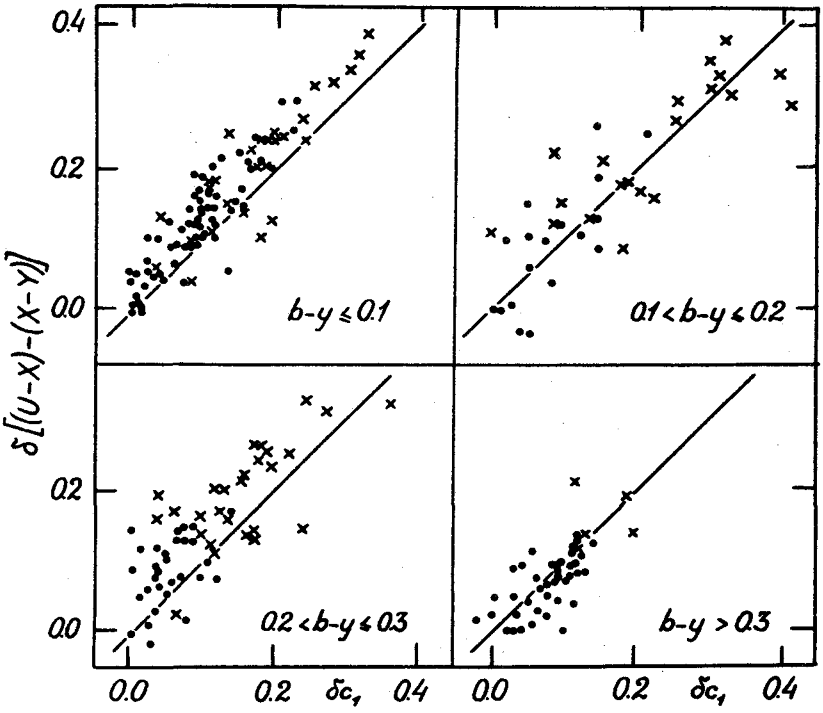

Fig. 4. The dependence of log g effects on the (U-X)-(X-Y) and c_1(b-y) diagram for different intervals of (b-y).

log g. This was done by two different methods by using individual stars with MK spectral types and M_V determined by other methods and by transfering the calibration in M_V of the MK system. The relations of spectral types determined from our Q, Q diagrams and of MK spectral types show a mean square dispersion ± 0.8 of a spectral subclass. The relation of M_V determined from photometry, with M_V determined by other methods, shows a mean square dispersion ± 0.58 for luminosity V-III stars and ± 0.90 for luminosity I-II stars.

To summarize, we conclude that calibration problems of photometric systems are far from being solved. The calibration will be considered as good only in the case when we use model stellar atmospheres representing real stars with much better accuracy than we have now. On the other hand, the improvement of accuracy of spectrophotometric determinations of temperatures and log g of real stars should be achieved.

Now let me say some words about standardization of intermediate band photometric systems. At the present time a number of such systems are in use. They include the Strömgren's uvby system, the Geneva observatory system, the Mitchell-Johnson system, the Vilnius system and the DDO system which actually is not a purely intermeddiate band system since it includes some narrow band magnitudes. All the systems are useful providing exact data on energy distribution for different stars in different parts of spectrum. However, the usefulness of photometric systems in this respect is losing its ground with the increasing number of stars with detailed energy distribution curves determined by photoelectric scanning. On the other hand, the appearance of new photometric systems is a somewhat negative phenomenon because of the necessity of repeating observations of a great number of well investigated stars in every system as standards and for calibration, and this requires a considerable amount of valuable observational time. At the same time many stars remain uninvestigated. In addition, it should be noted in most cases the results of observations in one system cannot be transformed into another system because of nonlinear and multivalued relations between them.

It would be good indeed to have a set of internationally accepted optimum spectral bands which could be used in different combinations for different tasks. Such a set could be founded on the basis of the existing photometric systems and some bands could be selected additionally. For instance, the ultraviolet magnitude response curve is very close in the uvby system, the Geneva system and the Vilnius system. The same situation exists near the break point of the interstellar reddening law where magnitude b of the uvby system, magnitude B_2 of the Geneva system and magnitude Y of the

Vilnius system are close to each other. We can find also other magnitudes repeated in different photometric systems. I suggest that photometrists discuss the problem of unification of systems as soon as possible. We should remember the great scientific effect made by the UBV system which unified scattered efforts of different investigators. An international intermediate band system with exactly defined response curves, with proper transformations to outside the atmosphere, with an exact and numerous set of faint standards and with a good calibration would give an even greater scientific effect. It would give the possibility of determining temperatures, gravities, luminosities, metallicities, peculiarities and interstellar reddenings for the stars as faint as 17-18^m, which are inaccessible by other methods. Measures in the system should be able to be made by photography, electronography, TV-techniques and diode arrays.

Together, with Geneva and Lausanne astronomers, we have started investigations directed to join the Vilnius and Geneva systems into one system having the best properties of both these systems. The first variant of the joint system called "Vilgen system" was realized and tested in the Vilnius observatory and described in my monograph. We also hope to be supported by the Basel astronomers. I call also the representatives of Strömgren system to join us.

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DISCUSSION

Philip: Your comparison of values of log g obtained from the four-color and Vilnius system is just what I would expect. In the Philip Miller Relyea catalogue (Dudley Observatory Report No. 12) the values of log g were quoted as having rms errors of ±0.2, so your finding a dispersion of ±0.15 agrees very well with this estimate.

The difference in the log g estimates for high luminosity stars is not surprising. In this region of the HR diagram there are very few standard stars with well determined values of log g with which to compare the log g values derived from the photometric indices. Dr. Hayes, of Arizona State University, and I have started a project to scan, photoelectrically, fifteen field horizontal-branch stars, which have log g values in the range of 3.5 < log < 2.0. The stars will be matched to the most recent atmospheric models to derive accurate values of log g and temperature. At the same time these stars are being set up as standards in the Strömgren four-color system. In a year's time we will have a number of well calibrated points to be used as checks on the transformations from photometric indices to values of log g for stars of higher luminosity.

Mendoza: Can you give the physical parameters of a star from only your photometry, not having any knowledge about the spectral type? If the answer is yes, please give as an example the T_e and g values of α PsA, 78 Vir and 63 Tau.

Straižys: Yes, we can. The system was developed having this task in mind. Considering the stars you mention I am sure they are bright enough to be classified spectroscopically. Two of them are peculiar and we cannot determine log g values for them. We make quantification in temperatures and log g only for normal stars. For Ap and Am type stars we can estimate only temperature, but not gravity.

Houziaux: One should recall that there are other parameters than the effective temperature and surface gravity.

I would like to know with what accuracy you know the response curves of your filters? What sort of accuracy do you get in computed colors?

I wonder also how you obtained the effective temperatures and gravities of the "real stars"?

Straižys: We tried to determine the response curves of the system as exactly as possible. When you use these curves to compute theoretical color indices you are influenced by errors of the response curves, energy distribution curves and the errors introduced by the width of the integration steps. I estimate that the errors of computed color indices are of the accuracy of ±0.02.

The effective temperatures and gravities of the "real stars" were obtained by averaging for every MK type the spectroscopically determined values of T_e and log g collected from the literature.

Houziaux: Are you able to determine monochromatic fluxes from your multicolor filter photometry?

Straižys: Monochromatic fluxes from our photometry could be determined using absolute calibration constants given in my monograph Multicolor Stellar Photometry. So determined absolute fluxes can be plotted at λ_0 to obtain rough energy distribution curves of the star.

Nandy: Have you compared your values of temperature for the same stars for which Code has determined the effective temperatures from angular diameter measurements and energy distributions from the visible to the ultraviolet? To check your temperature scale, this comparison would be very useful.

Straižys: Yes, we have used Code's stars to calibrate our parameters Q in temperature for early-type stars. Actually our temperature scale is completely based on Code's results.

Philip: Dr. Nandy has made an important point. When the transformation from $(b - y)_0$, $(c_1)_0$ to log g, Θ_{eff} was being made in the Philip Miller Relyea catalogue, I was interested in checking the derived temperature calibration. There were 27 stars in the literature for which temperatures had been derived spectroscopically (this was before the Code, Bless, Davis, Hanbury Brown article had appeared). When the residuals, temperature published minus temperature calculated, were plotted versus temperature, it looked as if there might be a systematic error of a few hundred degrees. But when the Code et al. article appeared I did the same calculation for all the main sequence, early-type stars in that list and the average difference in temperatures was zero. So the difference was not due to the photometry or the transformation from indices to temperature, but rather in the older published spectroscopic results.

Krawczyk: You have spoken mainly about the calibration problems of your system. I would like to ask you for how many stars you have obtained the Vilnius magnitudes and can you say something about the distribution of these stars on the sky? Are you going to undertake any sky survey in the Vilnius system?

Straižys: We have observed approximately 2500 stars in the Vilnius system. About 1200 of them are bright stars scattered over the whole sky and they were observed for calibration purposes. Other stars are mostly faint stars observed in different areas of the Milky Way with the aim of determining their two-dimensional classification, interstellar reddening and the reddening laws. Some areas are at high galactic latitudes near the NGP. Dr. Bartkevicius and others have observed some hundred population II stars (subdwarfs, metal-deficient giants, hot subdwarfs, horizontal-branch stars, etc.). They have found some new stars with extreme metal deficiency. A number of stars were observed im some SA areas at +30° and 0°. We have no plans for a sky survey but we try to observe the faintest stars we can reach for which it is impossible to obtain spectra for MK classification.

Gratton: Are you also contemplating the use of clusters for calibration purposes?

Straižys: Open clusters of different ages (i.e. Hyades, Pleiades, Orion association) were used to determine the ZAMS in the Vilnius system diagrams. The system later was applied to investigate some open clusters in Cygnus trying to test their reality. We have made also an integral photometry of a number of globular clusters trying to classify them by photometric properties.

Gratton: Of course the integrated light of globular clusters has the great drawback that the contribution to different wavelengths does not come from the same stars.

Code: It is not clear to me how you take account of variations in the law of interstellar reddening?

Straižys: We usually compare color indices of two stars of the same spectral type with different amounts of reddening. Another method is to use the slopes of reddening lines of the stars of the same spectral type (O-type stars usually) in two color diagrams.

Oja: To what extent will it be possible to discriminate between single stars and unresolved double stars from the photometric data alone?

Straižys: The effects of unresolved binaries in the Vilnius system were investigated by Dr. Kakaras and myself some years ago (Bull. Vilnius Obs. No. 23). The discrimination possibilities strongly depend on the difference between the magnitudes and spectral types of components. For instance we cannot detect duplicity for stars when both components are main sequence objects. For such double stars the spectral types and magnitudes are interconnected and when magnitude difference decreases the spectral type difference decreases as well. Good detection of double stars is reached when one component is an early type star of luminosities V-III and the other component is a late type giant or supergiant. Pairs of supergiants of different colors are also easily recognizable. I should mention that all the distinguishing of double and multiple stars is achieved on Q,Q diagrams and so recognition does not depend on the interstellar reddening. Double stars can be recognized either by their specific positions on Q,Q diagrams where no single stars can be found or by analyzing their behavior in different Q,Q diagrams where they change their position with respect to normal single stars.

Coyne: I am surprised that you speak of detecting variations in the reddening law with this photometry. Is it not true that the major variations in the reddening law are found at wavelengths longer than 1μ?

Straižys: Certainly, the most significant variations in the interstellar extinction law occur at infrared wavelengths. However, some small variations in the form of the extinction law can be found also at visual wavelengths, especially in our magnitude S (6560 Å) and in violet and ultraviolet magnitudes U, P and X (3550, 3740 and 4050 Å). The variations of the extinction law at short wavelengths is possibly connected with the variations of intensity of the 2200 Å peak which is observed by orbiting observatories. The regions in which we find differences from the normal extinction law are in Cygnus and in the Opiuchus dark clouds.

Wing: I do not think we need be so concerned about variations in the interstellar reddening law in the infrared. Most of the evidence for such variations that accumulated around ten years ago has been shown, I think, to have been the result of comparing stars with shells to stars without shells.

Straižys: The investigations of the interstellar reddening law during recent years made by different methods: photoelectric scanning, photographic spectrophotometry and by multicolor photometry, show that this law differs for different stellar groups. This cannot be explained by circumstellar shells. The variations are found in all parts of the spectrum, from the infrared through the visual up to the far ultraviolet. The variations of the law are reflected by variations of the ratio R = A_V/E_{B-V} which is found to vary between 3 and 6. The regions of increased ratio R are connected usually either with stars in emission nebulae or with stars embedded into dense dark interstellar clouds. In both these cases the size of interstellar grains is increased.

Divan: The differences in interstellar reddening between the Cygnus and Perseus regions amount as you said to 0.05 in the ultraviolet magnitude. These differences are due to systematic differences in the Balmer jump of O stars in Cygnus and Perseus, due to differences in luminosity class. Where the reddening law is investigated by a method that avoids this type of error, the two reddening laws in Cygnus and Perseus appear identical in the visual and ultraviolet regions.