VIII SPACE SPECTROSCOPY AND FUTURE DEVELOPMENTS IN CLASSIFICATION

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FUTURE DEVELOPMENTS IN CLASSIFICATION

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ABSTRACT

Future advances in spectral classification are considered in terms of the likely effects of the following four factors: 1. observation from space; 2. new instrumentation developments; 3. modern data processing techniques; 4. the impact of new observations and astrophysical theory.

Classification will be carried out over an extended spectral range from the vacuum ultraviolet into the infrared. Both because of improved detector sensitivities and the use of space telescopes, spectral observations will be pushed to fainter limiting magnitudes. The assimilation of this expanded set of data will be aided by, and indeed demand, the application of sophisticated data handling techniques. Classification criteria will be developed to encompass additional parameters suggested by theoretical investigations, and spectra classification systems will be formulated to systemize the studies of such diverse objects as stellar coronas, protostars, QSO's and galaxies, for example. This paper discusses specific directions that spectral classification may take within the above conceptual framework.

Modern astrophysical advances have been characterized by the synthesis of observations carried out over the entire electromagnetic spectrum. Space spectroscopy cannot be fruitfully discussed in isolation. Rather I have chosen to emphasize future developments in classification with the addition of space observations and the methods that have been accelerated by the application of space techniques. It is, of course, difficult to forecase the future but such

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speculation has at least one advantage. I do not need to know just how to do what I suggest nor fully understand it. That is for imaginative minds of the future with more sophisticated instrumentation and a larger body of facts on which to build.

I believe that spectral classification has a future, at least in some generalized form. I take as both the definition of spectral classification and its purpose the systematic ordering of celestial objects from their spectral characteristics such that if properly done members of the same class all share common physical properties and thus we do not have to separately understand each individual member.

Among the factors that will significantly influence future advances in spectral classification I have singled out the following: (1) observations from space, (2) new instrumentation developments, (3) modern data processing techniques, and (4) the impact of new observations and astrophysical theory.

The ability to carry out measurements throughout the entire electro-magnetic spectrum leads naturally to the development of classification criteria that emphasizes different characteristics or physical processes. The infrared and millimeter region yield information on low energy phenomena. It is, of course, the realm of molecular transitions and the region of energy maximum for cool sources. We shall certainly wish to systematize the characteristics of proto stars and cocoon stars and further understand their generic relation to dense molecular clouds from which they come. The relative transparency of interstellar space in the infrared promises to extend classical studies to greater distances in our galaxy. Infrared spectroscopy has something to tell us about hot stars also. For those stars with significant mass loss the extension to longer wavelengths allows one to probe further and further out into the expanding envelope. Spectral lines in the far infrared will yield the asymptotic velocities of the wind. The radius to an optical depth of 2/3 in a model of the envelope of ζ Puppis is shown in Fig. 1. The free-free opacity increases as λ^2 and by 10μ's the effective radius has increased by 15%. Other envelopes can show more dramatic changes.

The vacuum ultraviolet, in the 10 electron volt range, is where the strong resonance lines of light ions occur. It is in fact these lines that provide the best data on stellar mass loss. The bulk of the energy for stars earlier than A0 is found in the region of the ultraviolet available to space telescopes. It was natural to ask, whether or not the small fraction of radiation observed from the ground for hot stars adequately represented the essential characteristics of these stars. Strong ultraviolet line blanketing can

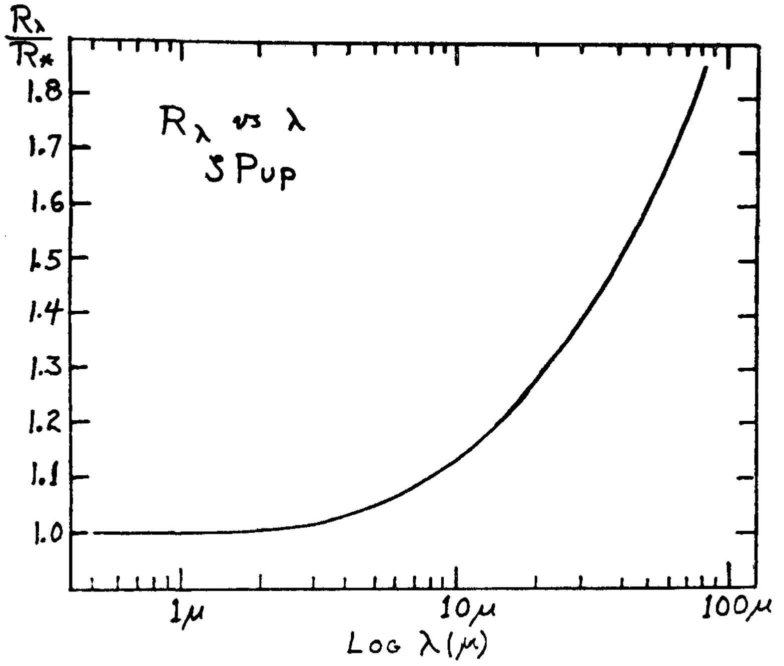

Fig. 1. Radius to an optical depth of 2/3 vs wavelength in a model of the envelope of ζ Pup.

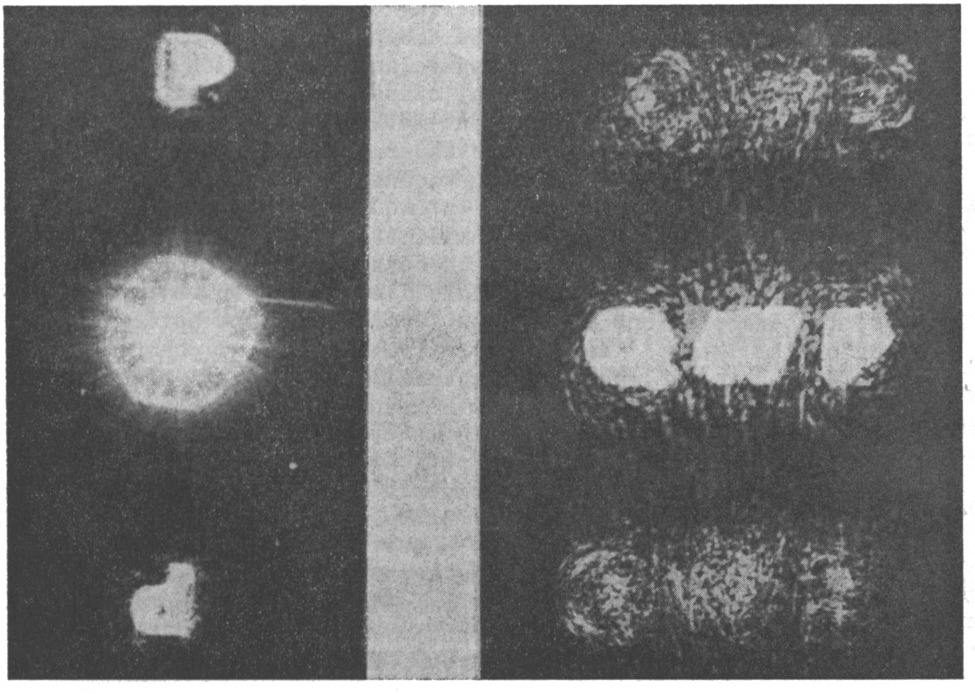

Fig. 2. (left) Impulse response of Vander Lugt filter to character "P". (right) Response to letters Q, W, P. Cross correlation is on bottom, bright spot at letter P indicates high cross correlation.

transfer radiation to the visual that might seriously modify the spectral characteristics. In general it is found that the spectral lines in the visual are more representative of the gross atmospheric structure than are the colors. Ultraviolet observations of cool stars provide an entirely different probe into the atmospheric structure. Shortward of 2000 Angstroms we primarily observe stellar coronas. I shall return to ultraviolet classification presently.

Recent improvements in detector technology are continually increasing our capability to observe to fainter magnitude limits. We are extending spectrographic studies to objects in other galaxies and to low luminosity stars in clusters and beyond the general solar neighborhood. Among the low luminosity stars are those that were formed in the early history of our galaxy and those low mass stars that are still in the process of migrating to the main sequence.

The new detector development will greatly increase the rate at which data is accumulated and in general will be generated in a digital format. Only by the application of currently formidable data analysis techniques can we efficiently assimilate this flood of data. The data analysis field is, of course, one that is currently experiencing an explosive growth and we must look to these advances for help. We have heard of some techniques for automatic spectral classification and of modeling by synthetic spectra. We can expect to batch processes large amounts of data to increase our statistical basis for understanding galactic evolution. Let me illustrate one approach to spectral classification that may be worth consideration. It is clear that one method of matching the spectrum of an unknown to the appropriate standard would be to form cross-correlation coefficients between unknowns and standards. The largest cross-correlation coefficient would represent the best match and hence the assignment of a classification. This can be done digitally, of course, and may be the best approach to cross-correlation. With large sets of data obtained currently on objective prism plates, for example, one might consider the coherent optical processing of the image. The plate is illuminated by a coherent laser beam. The scattered light then represents the fourier transform of the images. This may be spatially filtered by an appropriate mask before reimaging. By the use of a Vander Lugt filter for a particular set of standard spectra the optical output can yield cross-correlations directly. While considerably simpler the pattern recognition problem is similar in nature. The use of a Vander Lugt filter to optically obtain cross-correlations is illustrated in Fig. 2 (from Goodman 1968). The transmission of the Vander Lugt filter contains the amplitude and phase information for the letter P. The photograph on the left shows the response to a point source. The response to the letters Q, W, and P is shown in the picture on the right. The upper image is the convolution integral. The significant feature of the picture is the bright dot in the position of the letter P. The extension of such techniques to spectral classification can take a variety of forms including real time operation at the telescope without the intermediate step of obtaining a plate.

High speed digital computers have to date been of even greater importance in producing substantial advances in astrophysical theory. Model atmospheres and interiors, while still primitive, have had a profound influence both on our understanding of stars and on the types of observations we currently make. Studies of stellar evolution have lead to the addition of an abundance parameter to our classification system. Spectral classification will continue to be modified by our increasing insight. Father Secchi's classification was carried out in the same spirit as modern systems but in the absence of any substantial theoretical framework it could not recognize a temperature sequence much less a two dimensional system. MK types and narrow band systems will necessarily evolve too. Theory has suggested a variety of other parameters that we may find necessary to introduce into classification systems such as mass loss, coronae, perhaps rotation, magnetic fields and diffusion.

Let me now comment in a bit more detail on a few of these directions. I shall return now to ultraviolet spectral classification.

As data on the ultraviolet spectra of stars has accumulated several investigations of spectral classifications have been initiated. Using objective-prism spectra from Skylab Henize et al. (1977) have carried out two-dimensional classification based on C IV (1550 Å) absorption and the ratio of Si IV (1400 Å) to C IV. Bidelman (1977) has examined the much higher resolution Copernicus spectra for classification purposes. The most extensive ultraviolet classification, however, has been of TD1-A, S2/68 spectra. Cucchiaro et al. (1976, 1977) have classified approximately 1500 stars from early B through F-types from criteria established in the wavelength region from 1350 Å to 2550 Å. Of this you will hear more in a subsequent paper at this colloquium (Cucchiaro 1979). By way of orientation, however, let me illustrate the main spectral features apparent in the ultraviolet at resolutions of the order of 10 Å. A portion of the ultraviolet spectrum of main sequence stars from O9 through B1 from OAO-2 spectral scans is shown in Fig. 3. These plots show the flux per unit wavelength interval, and show the shortward rising continuum and the behavior of the strongest lines and blends as a function of MK type. The systematics with type and luminosity class can perhaps be seen better by displaying these

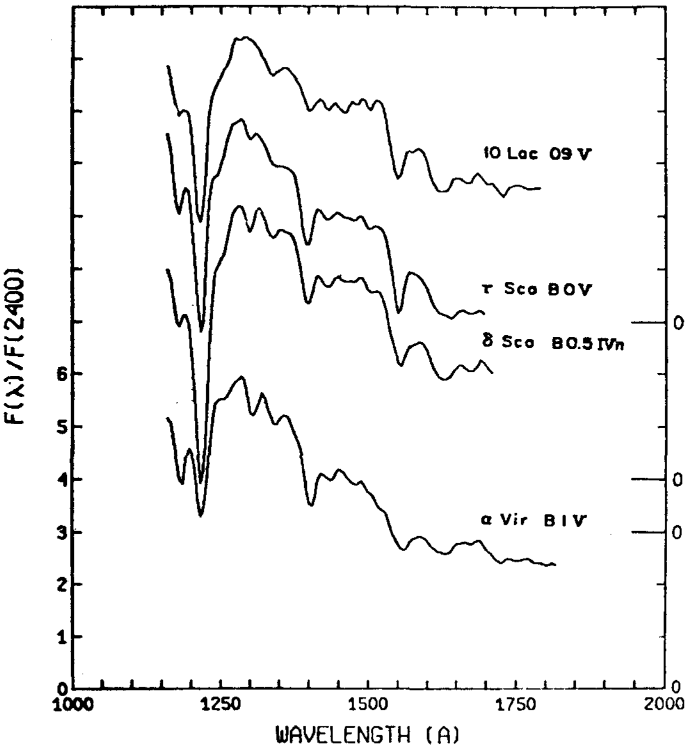

Fig. 3. Ultraviolet flux of main sequence stars 09 through B1 from OAO-2 spectral scans (Code & Meade, 1979).

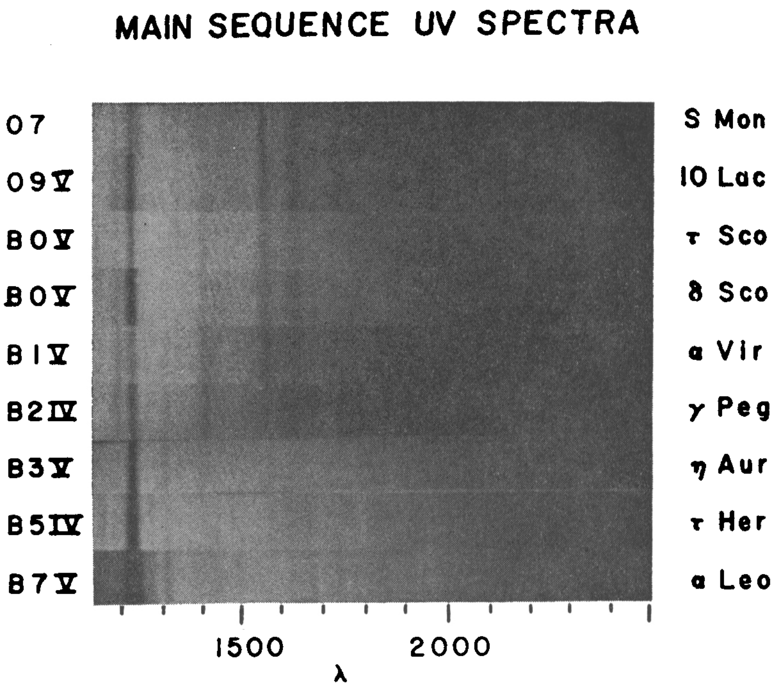

Fig. 4. Photographic display of ultraviolet spectra of 07V through B7V stars.

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scans in a photographic form. The main sequence from 07 through B7 is shown in Fig. 4. The strongest feature is, of course, the hydrogen Lyman α line, which is primarily interstellar in the earliest types and primarily stellar in the later B stars. The strong resonance lines of Si IV and C IV are the next most dominant features. Both lines are sensitive to luminosity and in the O stars and early type supergiants these resonance lines have a P Cygni structure and provide evidence of mass loss. The Si III, Si II blend at 1300 Å and the features at about 1260 and 1340 Å are good spectral type indicators in the later type B star. Luminosity effects at 09.5 and B0.5 are shown in Fig. 5. While the Si IV and C IV lines increase in strength with luminosity the most sensitive features are the blends centered about 1620 Å and 1720 Å (Underhill, Leckrone, West 1972). Later spectral types display a number of sensitive blends which permit extension of the classification through the G stars. Among the A-stars, ultraviolet classification isolates Ap and Am stars quite effectively. The spectra of F and G stars in the neighborhood of the Mg II (2800 Å) doublet are shown in Fig. 6. Mg II increases in strength through the sequence while Mg I becomes prominent in the G stars. Throughout the F and G stars a sharp discontinuity is present at about 2610 Å in all luminosity classes. This discontinuity as well as one near 3210 Å are apparent in highly redshifted galaxies. At this resolution the Mg II doublet weakens with luminosity because the Mg II emission fills in the line until late type giants and supergiants display strong emission at 2800 Å. Shortward of 2000 Å observations of late type stars are essentially coronal in nature and are currently being actively studied with IUE.

I would like to make some general comments with respect to spectral classification in new wavelength regions. The first obvious comment is that such classifications do not replace, but supplement, traditional systems such as the MK system. If the results are discordant and both classifications are done properly then the result is telling us something new. Secondly, a point emphasized by Bidelman, while in some cases it would appear that a more accurate two-dimensional classification can be obtained in the ultraviolet for example, in a given range of types, this may not be true. Rather the line ratios may be more sensitive to chemical composition or mass loss or some other physical parameter. That is the extension of the spectral range opens up the opportunity to introduce the other dimensions in our classification of stellar spectra. Finally I would like to make some remarks that I suspect W. W. Morgan would make were he here. Any classification system should be internally consistent and based only upon the observed spectral characteristics in the relevant spectral region and in principal use the information content available throughout the entire spectral region. It must not utilize information on colors or

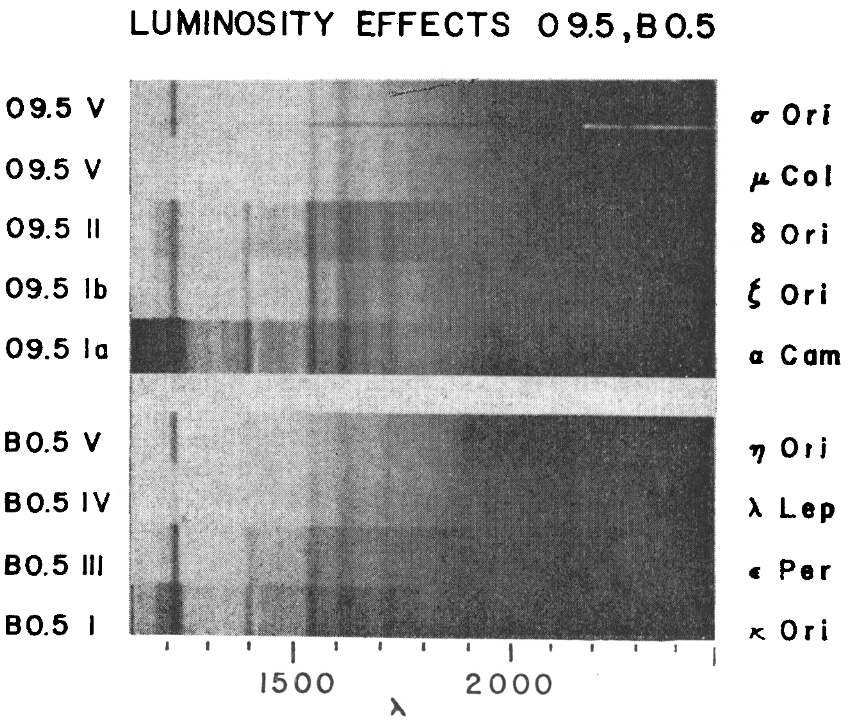

Fig. 5. Luminosity effects at 09.5 and BO.5.

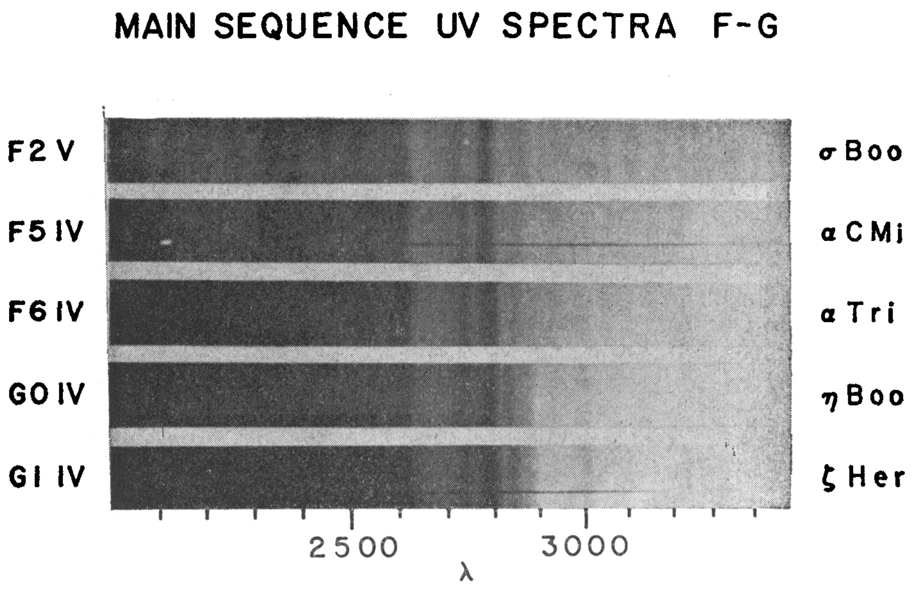

Fig. 6. Ultraviolet spectra of main sequence F and G stars.

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traditional spectral types. The system also should be independent of the specific data set employed. That is it should be reproducible by another observer using different instrumentation, resolution and calibration techniques. None of the current ultraviolet classification systems are fully satisfactory from this standpoint. It is not possible to obtain the same values for flux ratios, equivalent widths or eye estimates of line strengths from Skylab objective prism spectra, OAO-2 spectral scans, Copernicus high resolution spectra or TD1 stellar spectra. The classification system must in the long run be defined by a set of standard stars, which then is the system. The relevant line ratios, etc, are simply guides to the iterative processes of matching the entire spectrum of an unknown with the proper standard. The standards must be established within their own regime. MK standards will not serve. As an extreme example the ultraviolet spectrum of Antares is shown in Fig. 7. It is of course primarily the spectrum of the companion, a B2.5 V star, and obviously a very poor M1 Ib standard. Antares is of course an example of a composite spectrum and indeed the extension of the spectral range provides great leverage in separating the components of multiple systems. The extension of the study of composite systems to the integrated light from objects such as globular clusters and galaxies provides useful data for characterizing the population of these objects. Mayall (1946) first reviewed the range of spectroscopic characteristics exhibited by globular clusters that was similar to that exhibited by weak line high velocity stars and cluster type variables. He also noted that those clusters near the galactic center averaged later in spectral type than elsewhere. Morgan (1956) investigated the dependence of the degree of metallicity on distance from the galactic nuclear region. Baade suggested that this correlation was actually one of distance above the galactic plane and not galacto-centric distance. Morgan (1959) developed a classification system in the blue-green using the intensity of the G-band, metallic lines and the difference in intensity of the continuum on either side of Hζ. Morgan classifies globular clusters into one of eight metallic line groups, I through VIII in order of increasing line strength. He points to the problems inherent in classifying composite systems and the ambiguities that may exist. Again the extension into other spectral regions provides a means of removing some of these ambiguities. The synthetic spectrum of the giant branch and the horizontal branch for a globular cluster like M3 is shown in Fig. 8. The spectra were formed by summing the spectra of an appropriate mix of single stars. As expected the horizontal branch makes the major contribution at shorter wavelengths and the giant branch longward of 3000 Å. It is perhaps not fully appreciated how strongly the sample varies with wavelength. A single faint blue horizontal branch star contributes as much light at 1500 Å as 1000 bright giants. The main sequence spectral distribution is

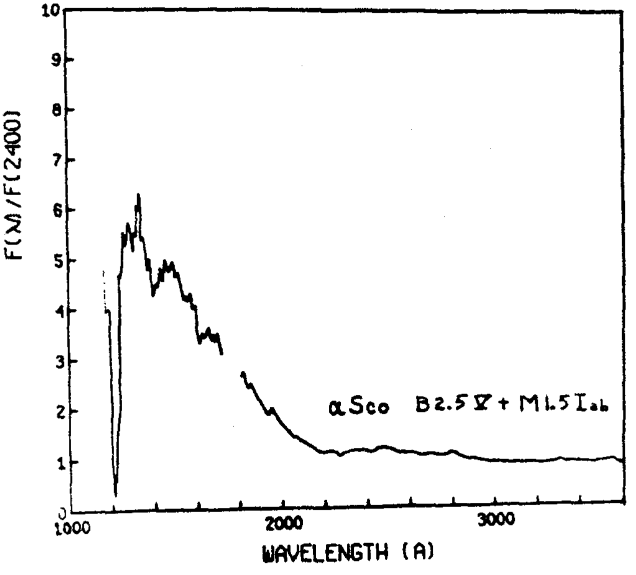

Fig. 7. Ultraviolet spectrum of Antares. The early type companion dominates.

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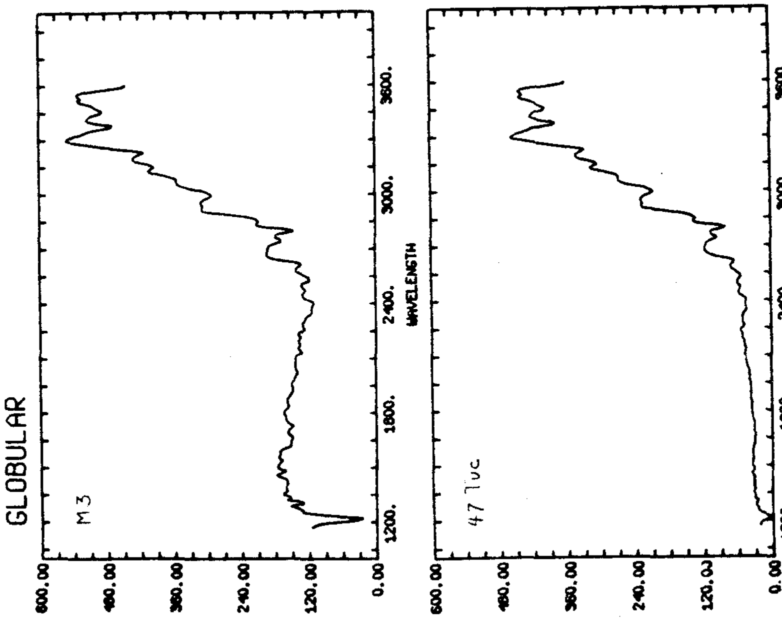

Fig. 9. Synthetic spectrum of the globular cluster M3 above 47 Tuc below.

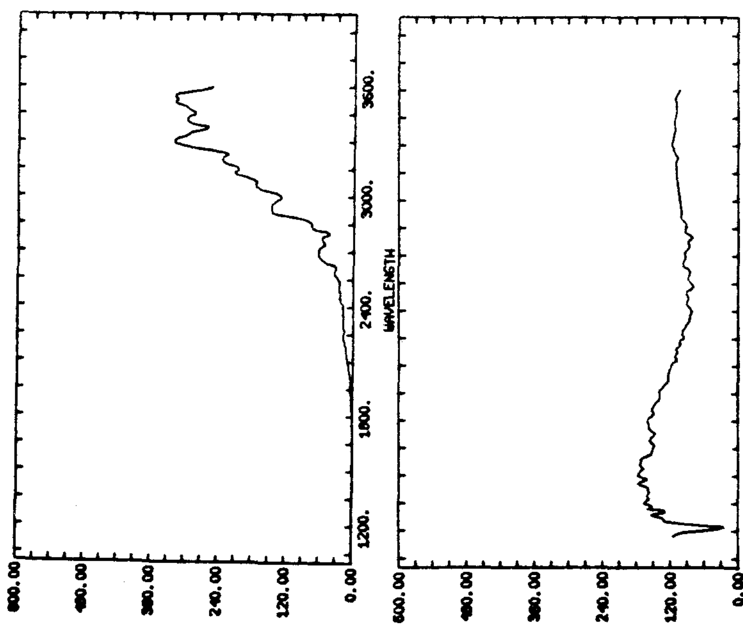

Fig. 8. Synthetic spectrum of a globular cluster giant branch upper & horizontal branch lower.

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similar to the giant branch but only about 20% as bright. Two synthetic globular cluster spectra are shown in Fig. 9. One is for a system with a strong horizontal branch such as M3 and the lower plot represents the energy distribution for the cluster 47 Tuc with only a stubby red horizontal branch. Now it is possible to use broadband colors to model the relative populations of the giant and horizontal branch but a unique solution including metallicity will require line spectra over a wide wavelength range. That the synthetic spectra I have constructed here may not be that far from reality is demonstrated in Fig. 10. Recently observations were obtained of several globular clusters with IUE by Gursky, Dupree, and Hartmann. A preliminary spectrum of M15 is shown compared with a computed synthetic spectrum. The next step is to obtain actual ultraviolet spectra of individual stars in globular clusters to perform more sensitive population synthesis. Then classification in different spectral regions will permit determination of populations and hence evolutionary characteristics throughout our galaxy and in other galactic systems.

I can of course repeat the discussion, above for spectral classification of the integrated light of galaxies. A truncated history of the development would again include the names of Mayall and Morgan (1957). Morgan has also developed a morphological classification scheme to be added to the Hubble types which reflects the general spectral features in the 3850 Å - 4100 Å region. In the case of spiral galaxies in particular not only is the spectrum highly composite and thus sensitive to the particular wavelength region but shows wide variations across the system. It is obvious in comparing classifications that either similar parts of the galaxy be used or the total integrated light. Spinrad and co-workers have used ultraviolet stellar spectra to synthesize the composite spectra of the systems as an aid to searching for lines or wavelength features in highly red shifted galaxies. This program has met with some success.

Malcolm Smith has described to you some of the properties of QSO's with $Z < 3$. Currently IUE is obtaining spectra of low red shift QSO's in the same wavelength region. It is important to determine the extent to which QSO's of different Z have similar spectra. To this end it would be useful as observational data grow to develop an appropriate classification system. P. Osmer (1978) has made a start in this direction on the objects reported here by Malcolm Smith. Osmer tabulates the equivalent width of Lyman α, the spectral index or gradient longward of Lyman α and the continuum discontinuities across the Lyman limit, D_L, and break shortward of Lyman α, D_C. Today we are still struggling simply to understand QSO's but eventually we will be concerned with differences between QSO's and the relation of these differences to the development and evolution of

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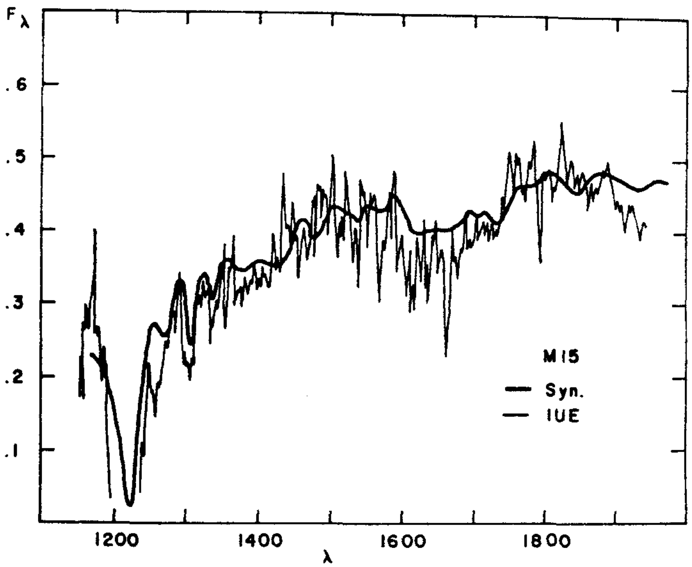

Fig. 10. · Comparison of a computed synthesis for M15 and a preliminary spectrum obtained by IUE (Gursky, H., Dupree, A., Hartmann, L. 1978).

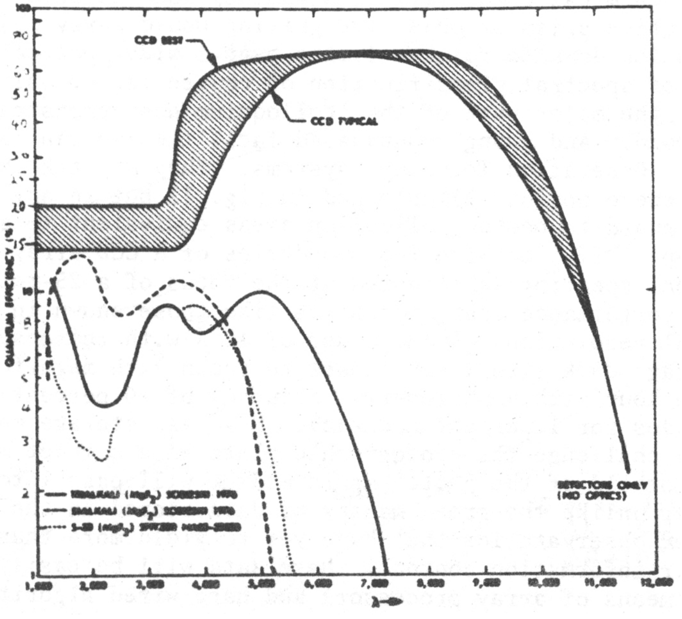

Fig. 11. Response of a thinned CCD and other common photocathodes.

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the quasar phenomena. At that stage at least it will be valuable to have placed the quasar within a framework of a good systematic classification scheme.

While the utility and scope of spectral classification will primarily be set by the astrophysical requirements, the manner by which this data will be obtained will be determined by the tools available and the innovations in instrumentation and data analysis employed by astronomers. I have already mentioned the progress in detector development. We can expect continued improvement in quantum efficiency, lower noise levels, higher photometric accuracy, greater resolution, and larger area. Currently single Si chip arrays like the CCD yield quantum efficiencies of 80% over a wide spectral range. The response of thinned CCD for Space Telescope application is compared with some other detectors in Fig. 11. Space Telescope itself, of course, is a major step forward. Free of atmospheric absorption and also the seeing problems that limit groundbased telescopes, it will be capable of observing over an extended spectral range, to very faint limiting magnitudes with high angular resolution. Space Telescope is to be launched by the Shuttle which also provides a platform for a variety of astronomical facilities in its Space Lab mode. The one-meter optical and UV telescope, Starlab, and the wide field survey instrument, DUVS, provide the opportunity for wide participation of the astronomical community. Instruments such as DUVS equipped with an objective prism or objective grating would carry objective prism calibration down to fainter limits over a wide spectral range. The future of spectral classification of course is not only in space but, as the major part of this colloquium has demonstrated, here on the ground. And among groundbased facilities we can look forward to the Next Generation Telescope systems. They may take the form of one of these options illustrated in Fig. 12 but in any event we can look forward to photon collection areas equivalent to a 25-meter telescope. If I combine the properties of a CCD array with an efficient spectrograph mounted at the focus of a 25-meter telescope, I find performance characteristics like those shown in Fig. 13. For spectral resolutions of the order of 10 Å with reasonable seeing and an average dark site I can expect to reach 24th magnitude in less than an hour with a photometric accuracy of 10 percent or about 21.5 magnitudes for 1 percent accuracy. New mass storage medium will finally challenge the photographic plate as a compact memory and the last foothold of the photographic medium will pass into history. Moreover unlike the great masses of data stored in the plate vaults of major observatories that have yet to yield more than a fragment of their information content, these data will be easily accessible. By the means of array processors and hard wired algorithms we can expect orders of magnitude increase in the throughput of digital computers.

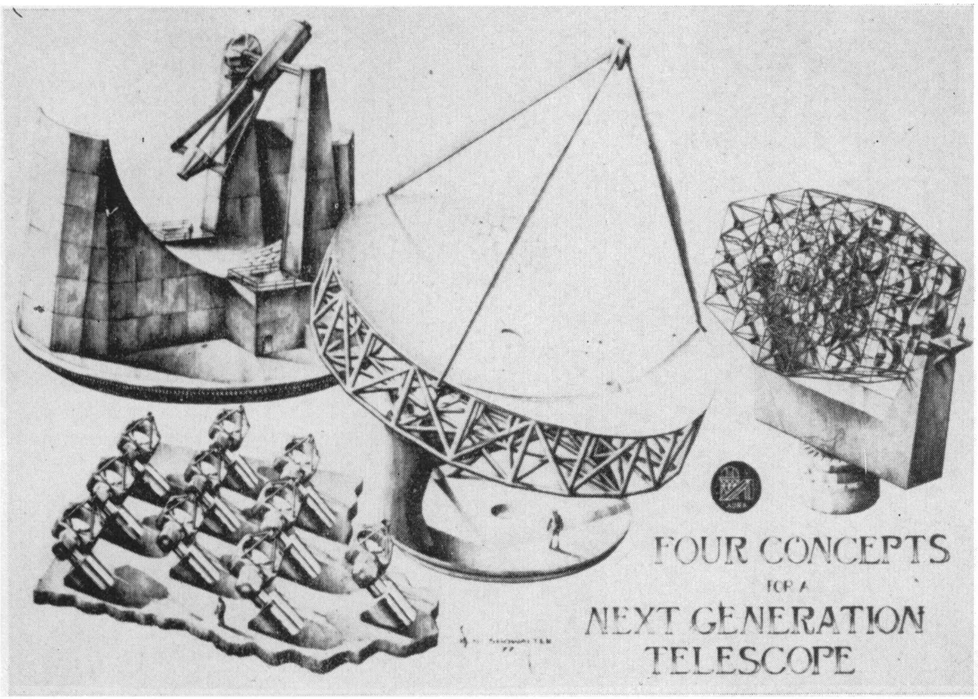

Fig. 12. Next Generation Telescopes-four concepts under study at Kitt Peak National Obs. for telescopes with collecting area equivalent to a 25 meter diameter telescope.

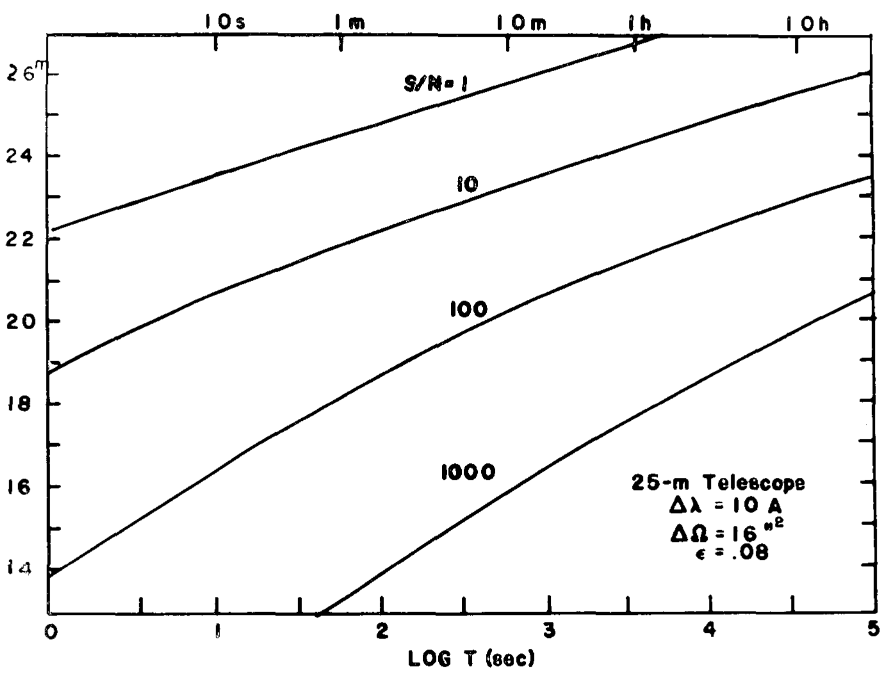

Fig. 13. Performance characteristics of a 25 meter telescope with an overall quantum efficiency of 8%, a 10Å bandpass and average dark site sky background and seeing.

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What I suggest this means for spectral classification is the following. Spectral information will be obtained over the entire accessible spectral range at moderate to high resolution and be available for any type of rapid processing desirable. If narrow band systems such as the DDO or Geneva or Vilnius systems retain their usefulness one certainly would not observe that way since it would be slower and would yield less information. (Of course it would also be less expensive.) Spectral classification of the future will, I suspect, retain the flavor of the MK system - that is, utilize all the spectral information available over the full spectral range.

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DISCUSSION

Jaschek: I am slightly worried about what shall happen in the rather near future — namely that we will get many satellite data (which cost dearly) for stars for which the corresponding ground data (to be obtained much less expensively) do not exist. What is being done about this gap? Are there special allocations for observing time at ground observatories for satellite observed stars?

Code: As we both know, many bright stars for which we have continuous spectral energy distribution in the ultraviolet do not have equivalent data in the groundbased spectral region and this is a problem. To date no special allocation of observing time, to support space telescope observations, has been committed by major groundbased observatories. It is an issue that has been continually discussed by astronomers active in the space telescopes program. Most study reports urge that NASA provide and support new groundbased telescopes dedicated to space telescopes. It is a role that the Space Telescope Science Institute should have a responsibility in also.

Garrison: Regarding the problem of space observations of objects for which no groundbased observations are available, may I suggest that lists be provided of stars for which data are needed. We are reaching the point at which general surveys are becoming tedious because of the numbers of stars involved is so large. Therefore, it will be easier to observe the stars for which data are needed than to provide the data beforehand.

Code: Spacecraft constraints often dictate what objects will be observed. So, in general, we do not know until afterwards what our groundbased needs are. However, any workers in satellite astronomy can provide you with a list.

Kharadze: What are the dispersion and resolution of the stellar spectra shown here?

Code: The spectrometer scanning slit for OAO-2 was 10 Å wide and usually stepped in discreet 10 Å steps. This yields a resolution of approximately 12 Å, half width at half intensity. The linear dispersion was, I believe, about 80 Å mm^{-1}.

Smith: The discussion of Code's paper has mentioned the difficulty of predicting likely discoveries. However one prediction can be ventured with reasonable confidence on the basis of Ariel V data

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by Ward et al. (Ap. J., 1978). They find a tight correlation between the X-ray luminosities of the Seyfert class I galaxies and apparent optical magnitude. HEAO-B will have 2-3 orders of magnitude greater sensitivity than Ariel V (see, e.g., Pounds, 1978, "New Scientist") and so large numbers of faint quasars should be accessible with that satellite. This will provide us with much needed independent access to the total QSO population.

Osmer used his "D_c" parameter as an estimate of the intervening neutral hydrogen between us and the QSO. It was intended to parameterize a data set taken with his own equipment, and as such adequately served his purpose. However, I feel sure he would not have suggested it as a general classification parameter for QSO's, as it may be a strong function of resolution, and difficult to reproduce elsewhere. If we do want such a classification parameter, then I would prefer the one proposed recently by Baldwin (private comm.) namely the total equivalent width for some defined wavelength region between Ly-α and Ly-β in the rest frame.

Code: You are probably right. "D_c" is not the best parameter but we should have a measurement of that effect.

Blanco: I would like to set the record straight in regard to the D_c values measured by Pat Osmer in the high redshift quasars. He did not use D_c as a classification parameter. Rather, he measured it simply to look into the possibility of evaluating the density of intergalactic neutral hydrogen.

Code: That is correct.