SPECTRAL CLASSIFICATION WITH ARRAY DETECTORS

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ABSTRACT. This paper presents the principles, the techniques, and some of the astrophysical potential of spectral classification in the era of array detectors.

1. REMOVING THE MYSTERY OF MK CLASSIFICATION

It is over fifty years since the MKK Atlas (Morgan, Keenan and Kellman 1943) was produced, and for about the first forty, photographic spectrograms dominated the way spectral classification was done. As in other fields of astronomy, the medium has shifted to digital spectra, witness "The MK Process at 50 Years" proceeding's lack of any photographic illustrations, save for the conference photo (Corbally, Gray and Garrison 1994). However, the spectral classification of stars, and in particular that based on the MK System, seemingly wrapped in the gloom of the photographic darkroom, might be thought of as a "black art" (Meyers-Rice and Young 1994) by those unfamiliar with its principles. In fact, the principles of spectral classification are essentially simple, the technique lends itself readily to array detectors, and its potential for astrophysical insight is enormous and enhanced by the digital array medium. I shall try to demonstrate these three points briefly.

1.1 The Principles

Spectral classification takes a morphological approach: that is, it starts with a good look at the specimen, the spectrum of a star. Thus, the classifier can fulfil *the mandate* of the MK System which is "to describe the appearance of the blue-violet spectrum of stars at moderate dispersion by reference to a set of standard stars (Garrison 1985)." The description uses *all* of the information in a stellar spectrum, not just certain ratios of line equivalent widths, and integrates it with a unique perspective. That perspective, sharpened by experience, may decide whether some slightly abnormal feature in a spectrum is significant or perhaps how best to characterize the astrophysics underlying a real abnormality. Thus, the description can complement other, more quantitative techniques, since it has a richness which numbers on their own lack.

The key to describing a spectrum is "by reference to a set of standard stars." So, the description is not arbitrary, but repeatable by different classifiers, whether human or machine (within the limitations of the latter). Garrison (1985, 1994) well describes the MK System's standards and their role in classification. In both papers Garrison makes the necessary point that the calibration of the MK System's classes in terms of temperature and luminosity are independent of the classifications themselves: so, if the calibrations change, the classifications do not.

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Setting up and maintaining standards takes research effort. It is worthwhile because fundamental astronomy comes out of careful spectral classifications. For instance, calibrations of the classifications in terms of absolute magnitude and color index lead to spectroscopic parallaxes. Calibrations in terms of T_{eff}, gravity, and composition provide initial input to stellar atmosphere syntheses. Surveys give us stellar populations, the signs of significant events in a galaxy's past. Detailed studies will isolate peculiar stars, and these peculiarities are often signs of significant events in stellar evolution.

1.2 The Method with Digital Spectra

Some corresponding effort, by way of precautions, is also needed by those who use the spectral standards in classifying program stars. In the days of photographic spectra, it was imperative, if the "look" of spectra was to be compared, to observe both standard and program stars in exactly the same way: same telescope, same spectrograph, same emulsion, same developer, etc. The advent of digital spectra has relaxed these requirements into just needing a similar instrumental profile and resolution for the final spectrograms that will be compared. One should be able to deconvolve a spectrum from the instrumental profile, but it is certainly easier to obtain that "similar profile" if spectra from intensified detectors are *not* compared to those from non-intensified detectors. Figure 1 compares an intensified CCD spectrum with that from a naked CCD, and there is a noticeable filling-in of lines for the former. This figure comes from a preliminary study by Garrison et al. (1991), without subsequent quantification of the effect, but it is sufficient to raise a caution over mixing spectra from different detection systems.

Photographic spectra were widened to achieve a high effective signal-to-noise ratio (S/N), and likewise, the S/N for the standards in digital spectra should be high, 200 or greater. It is always a pleasure, and besides aids accuracy (lowering systematic error) and precision (lowering random error), to classify the program-star spectra if they are also of high S/N, but these stars are generally faint and so a compromise in exposure time must be made. With digital spectra, it does not matter that the standard and program spectra have different S/N, since, providing that the standard spectra have high S/N so that the features in at least these are identified unambiguously, the accuracy and precision will depend on the S/N of the program spectra (e.g., noise added to the spectrum of a metal-weak, early A-type star's spectrum can simulate lines and so appear to be a slightly later spectrum). This contrasts with photographic spectra, which need to have similar densities on the plate for a precise comparison and so an accurate classification. (Bracketing exposure times for the standard spectra was a familiar procedure.)

The normal processing of digital spectra should also be done for those to be used in classification, i.e., bias removal, field flattening, wavelength calibration, fluxing (not required if spectra from the same telescope and instrument are compared), pixel binning. Obviously, final resolutions should be the same for standard and program spectra. Rectification (continuum removal) is needed for comparing spectra both by eye and by machine. The more carefully this is done, the easier and more accurate is the comparison, and so effort spent at this stage is usually repaid. Tools for rectification are found in such image-analysis packages as IRAF, but the Fourier division technique (LaSala and Kurtz 1985) can produce more consistent results than "by-hand" methods, though it still tends to "fit" the hydrogen lines, so "dragging" them upwards and altering their profiles. Perhaps the flattest spectra of all are produced via a

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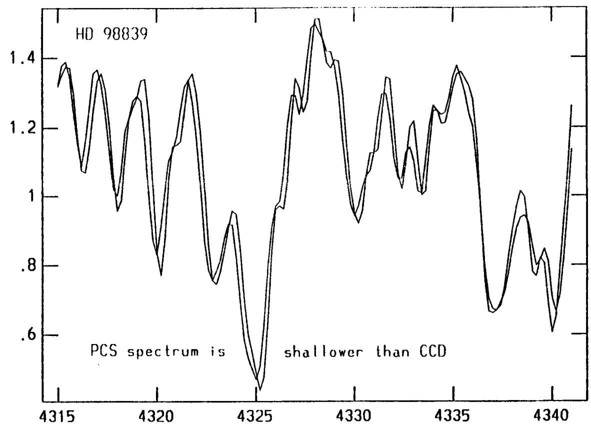

Fig. 1. Comparison of spectra from intensified (PCS) CCD and naked CCD detectors for the same star, HD 98839. The intensified spectrum is shallower than the naked spectrum (Garrison et al. 1991).

program of Richard Gray that uses a grid of synthetic spectra as templates, identifies the continuum points on the synthetic spectra, and then multiplies the observed spectra by factors that will bring those points up to the continuum.

With the digital spectra of both the standard and the program stars to hand, it is now time to see what insights and astrophysics can result from spectral classification.

2. CURRENT DIGITAL SPECTRAL CLASSIFICATION

The following account of advantages and highlights of classification with array detectors is based on the papers given at the MK50 workshop, and those whose interest is aroused are invited to read further in the proceedings (Corbally, Gray and Garrison 1994). The report of the IAU Commission 45 (MacConnell 1994) is a more comprehensive, if compressed, account of current classification work.

2.1 Accessibility of UV and IR

Papers in this Symposium (e.g., Vanzi et al. 1995) have shown how spectroscopy has been given access to wavelength regions beyond the optical. The opportunities have not been lost on classifiers, though now not strictly producing "MK" classes since the spectra are out of the MK System's blue-violet region and 2 Å resolution. Two current "opportunists" are Walborn and Rountree. For instance, Walborn (1994), while first recognizing the O3 stars in the traditional MK region, also finds that they are a class clearly separated from the O4 stars in the UV, based on their wind lines (Fig. 2). Their identification and analysis from the UV as well as the optical gives physical parameters for these, such massive stars (100 - 200 $M_\odot$, T_{eff} = 50 - 60,000° K) and information about their winds. Rountree (Rountree and Sonneborn 1994) has tackled the dwarf and giant B stars, and she has produced a UV spectral atlas for these which

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does not depend on the wind line strengths and is truly independent of, though happens to run parallel to, the MK System. Thus, Rountree has applied the "MK Process" (see Morgan [1984] for a definition) to a spectral region other than that used for the traditional MK System.

When we move in wavelength redwards of the MK region, we find Torres-Dodgen and Weaver (Torres-Dodgen 1994) making spectral sequences of, of all things, hot stars in the region 5500 - 9000 Å (Fig. 3). However, this makes sense for investigations of hot stars in regions of high extinction.

For M dwarfs it does make sense, more obviously, to move even further into the infrared, and so we find Boeshaar, Kirkpatrick and colleagues (see Boeshaar and Davidge 1994) working down to the two micron region, which is dominated by the molecular bands (e.g. TiO, VO, FeH, CO, and H_2O) though there are some useful atomic lines. Here (Fig. 4), the quest is to identify what features are sensitive to temprature and gravity, and the reasons for their sensitivities - as well as find the Holy Grail of brown dwarfs.

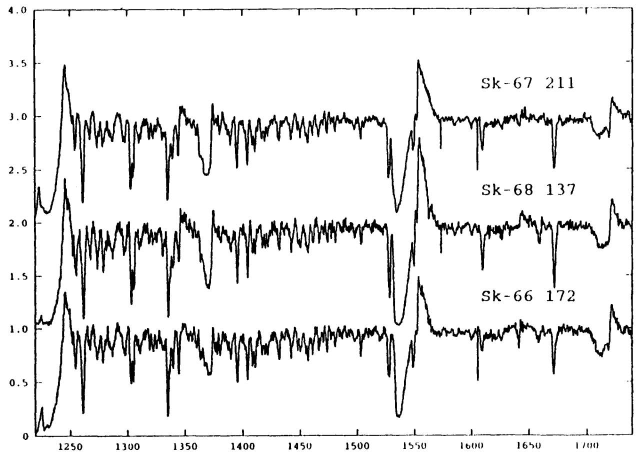

Fig. 2. Rectified HST/FOS spectrograms of three O3 III (f*) stars in the LMC. They show prominent wind lines (from Walborn 1994).

2.2 Precision Classification of Fainter Stars

Gray (1988) noticed that the hydrogen lines of λ Bootis stars, at classification resolution, divide those stars into two types, those with normal or with peculiar profiles. It is reassuring to find that this sometimes subtle distinction is readily seen in a digital spectrum such as Fig. 5. In this figure we find the first identification of a λ Bootis star in an association, that of Orion OB1, lending support to the theory that the mechanism for producing these stars is accretion from a circumstellar envelope with selectively weak metals (Gray and Corbally 1993). Levato et al. (1994) have announced the discovery of two more λ Bootis stars in Orion OB1,

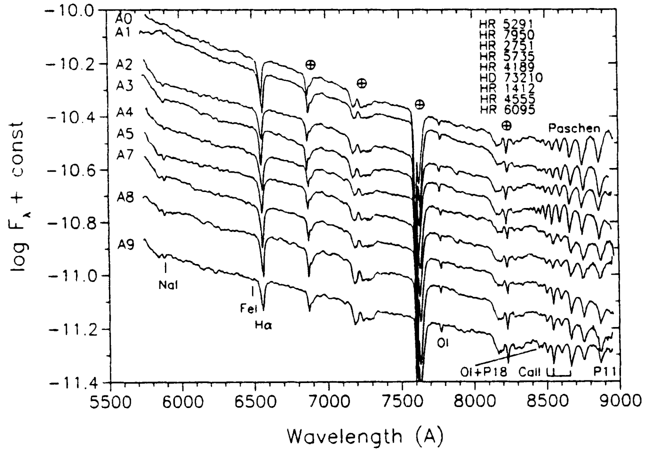

Fig. 3. Temperature sequences for A giant stars in the near infrared (Torres-Dodgen 1994).

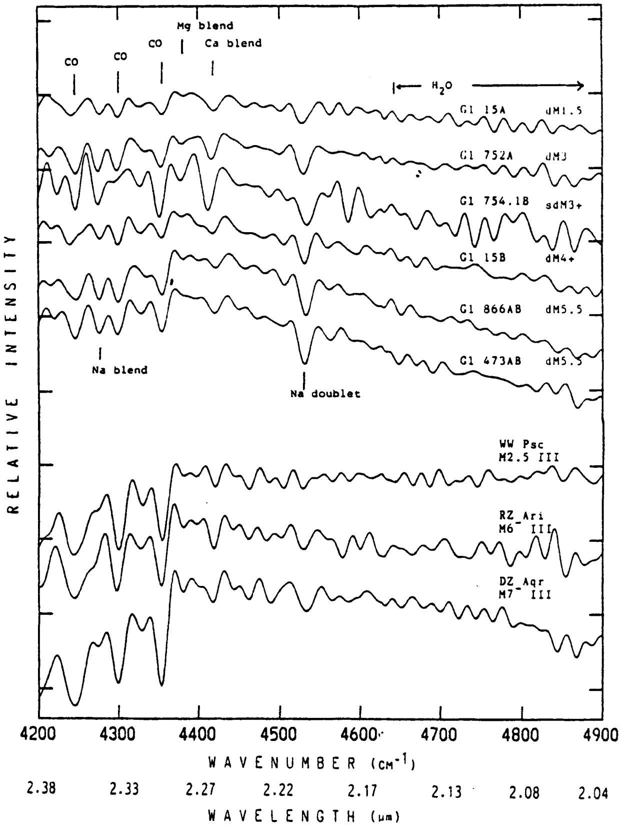

Fig. 4. K-band spectra of M stars at a resolution of ≈ 10 cm^{-1} arranged by luminosity class in order of decreasing temperature (Boeshaar and Davidge 1994).

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and currently work is in progress to search in other associations and young clusters to establish the duration of the phenomenon. The sensitivity of CCD detectors a great help in widening searches like this to fainter magnitudes, especially when the detectors are allied with multi-object spectrographs.

Digital spectra lend themselves immediately to comparison with synthetic spectra, as in Fig. 6 where helium-rich and helium-normal models are compared with a Field Horizontal Branch star (Corbally and Gray 1994). While the broad hydrogen-line profiles in the FHB star could be explained by a helium-rich atmosphere, the increased He I strength (not seen in the FHB star) makes the hypothesis fall down. However, this explanation may have more success in understanding the A-type supergiants with anomalously strong hydrogen lines that Humphreys et al. (1991) find in the Magellanic Clouds. The ease of comparing digital spectra with synthetic spectra also makes practicable a new way of calibrating MK spectral types with respect to physical parameters such as T_{eff}, log g, and [M/H] (Gray and Corbally 1994).

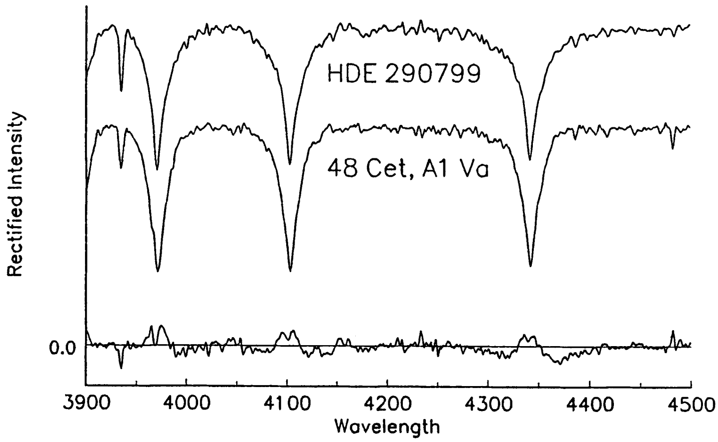

Fig. 5. The spectrum of HDE 290799, a λ Bootis star in Orion OB1, compared with the A1 Va standard. The slightly peculiar nature of the hydrogen-line profiles of HDE 290799 can be seen clearly from the difference spectrum at the bottom of the graph (Gray and Corbally 1993).

2.3 Automatic Classification

Digital spectra are in a form suitable for input into automatic classification, and I look forward to the time when I can drag the filename of a spectrum across a computer screen into a task box labelled "classification." If the computer returns "peculiar" for the spectrum, I shall then enjoy characterizing and investigating the peculiarities by eye, leaving the normal stars for the gathering of statistics. Two main teams are developing the tools to fulfil this dream, tools which are based on the pattern-recognition that is the essence of the MK System's mandate and power. One team employs a technique of weighted metric-distance (LaSala 1994), and the other uses artificial neural nets (von Hippel et al. 1994, Weaver 1994). Both methods are proving fruitful. The prospect for future surveys in and beyond the Milky Way, based on digital spectra, seems good.

2.4 Archiving and Dissemination

Since digital spectra need to be reduced before being archived, this involves more steps than for photographic spectra, which are "reduced" by being developed. While that extra reduction can seem a disadvantage, digital spectra have a clear advantage over photographic ones in their dissemination. Copies can be made and sent easily and are equivalent to the original. Thus, digital spectral archives can let one have one's cake *and* eat it (Griffin 1992). The IAU recognizes the great value of this through its support via Commission 29 of a Working Group on Spectroscopic Data Archives.

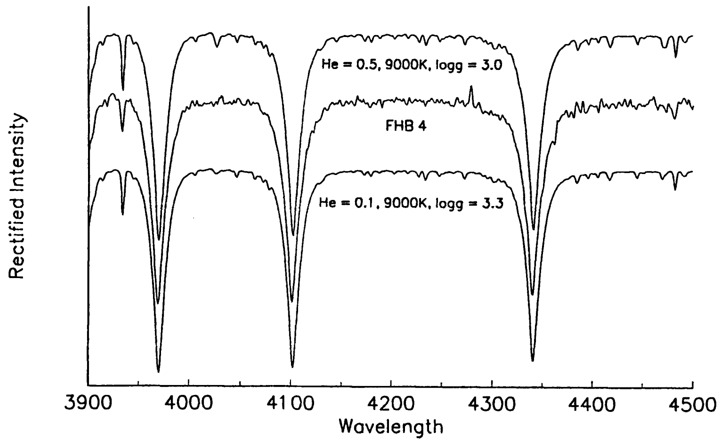

Fig. 6. Comparison of helium-rich and helium-normal synthetic spectra with a FHB star spectrum. Note the broad hydrogen lines (Corbally and Gray 1994).

3. CONCLUSIONS

The MK System lends itself to classification with spectra from array detectors as readily as from its original medium, photographic plates, providing similar care is taken to get consistent, high quality data that are anchored within a grid of the MK standards. We have seen that certain precautions are needed with regard to instrumentation, signal-to-noise ratio, and processing.

Some advantages apparent in current classification with arrays are: a) the ready accessibility of other wavelength regions; b) the opportunity to classify fainter stars than with previous media and still achieve precision spectral classification; c) the ease with which the digital medium lends itself to archiving, dissemination, and automatic classification of spectra.

So, thanks to new detector technology, things bode well for the science that will come from spectral classification in the next fifty years.

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I thank the authors whose Figures are shown here and draw attention to the fuller treatment of the Figures in the references. I also thank Richard Gray whose suggestions improved the final version of this paper.

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DISCUSSION

VERSCHUEREN: When referring to automated classification, is it possible to quantify all MK methodology criteria, e.g., through intensity or equivalent-width ratios of different lines?

CORBALLY: Yes. That first and simpler method of automating classification is called the criterion-evaluation technique. It is useful to a limited extent. I mentioned the newer, pattern-recognition technique since this is closer to visual classification and better.

GARRISON: The criterion-evaluation technique is antithetical to the MK methodology, which is much more powerful. Using a few line ratios quantitatively requires careful fluxing, with all of its problems. Pattern recognition over the entire spectrum includes the experience of the observer and easily isolates peculiarities, which may not be included in the quantitative ratios of the criterion-evaluation method, which is a very simplistic approach to a complex information system. Using quantitative ratios ignores a lot of interesting and important information. Using the entire spectrum in a pattern-recognition methodology, whether visual or automated, is certainly the way to go, leading more surely to discovery of new phenomena. People working in this area include Kurtz, LaSala, von Hippel, and Weaver. The first two use minimum metric-distance techniques and the last two use neural nets. With modern computers, there is no reason to use the overly-simplistic criterion-evaluation approach.

HOWELL: Chris, could you comment on your plot showing that the PCS shows "shallower" profiles than the CCD spectrum? How can you rule out that the cause is in the star itself? What effects for, say, temperature and gravity or MK classification itself, would these changes cause?

CORBALLY: Non-variability in the star itself can be ruled out by the choice of star, e.g., avoiding supergiants. For MK classification, the example of HD 98839 would probably have negligible effect, but I have seen MK-significant differences in spectra from Kitt Peak compared with those from Sutherland.

GARRISON: This was an experiment to see what are the effects of using a photon-counting detector versus a naked CCD. My interpretation of the difference, which is relatively small, is that there is some asymmetric scattering in the intensifier train. The two detectors were used on the same spectrograph, so the intensifier train is the only variable. If the scattering is perfectly symmetric, the centroiding should take care of it, but obviously there is some asymmetry. The effect is small, but if I were doing stellar atmosphere work, I wouldn't go near an intensified photon-counting system, but would stick to a naked CCD.

FLORENTIN-NIELSEN: If you do get a large number of suitable CCD spectra, could you conceivably apply neural networks to do the classification?

CORBALLY: Yes, as in the automatic classification work currently exemplified by von Hippel and Weaver.

WARREN: If you could get your hands on Hipparcos data for a large number of bright stars right now, what would you do with them in terms of calibrating the MK system?

CORBALLY: I should first pick out any supergiants with zero or low reddening, since they occupy the part of the HR diagram for which absolute magnitudes are difficult to calibrate and yet very much needed.

HOUK: Do you envision a survey of fainter spectra being done with CCDs rather than, say, with a four-degree prism? I'm referring to a large, if not all-sky survey.

CORBALLY: When large format CCDs become available on Schmidt telescopes, I should hope for such a fainter spectral survey. Meanwhile, LaSala's and von Hippel's project to classify automatically the non-HD stars on the Michigan spectral survey plates will prove a valuable extension of your own work.