INVESTIGATIONS OF CP AND NORMAL STARS WITH COADDED DOMINION ASTROPHYSICAL OBSERVATORY SPECTROGRAMS

Graham Hill
Dominion Astrophysical Observatory
National Research Council of Canada
Victoria, B. C. V8X 4M6 Canada

Saul J. Adelman[1,2,3]
Code 681, Laboratory for Astronomy and Solar Physics
NASA Goddard Space Flight Center
Greenbelt, MD 20771 USA

ABSTRACT. We describe the procedures developed at the Dominion Astrophysical Observatory to coadd high dispersion coude spectrograms and thus increase the signal-to-noise ratio in photographic data. These techniques can yield low noise spectra over a considerable wavelength range. Preliminary results of the analyses of such coadditions are shown to demonstrate the power of these procedures.

1. INTRODUCTION

Recently Cowley and Adelman (1983) examined the prospects for improved abundance analyses of CP stars and the normal B and A stars used as comparison standards. A major factor which will lead to such an improvement is the use of higher signal-to-noise data at high resolution. Much of this data is being obtained with solid state detectors, which usually are small and consequently can only obtain data over limited wavelength ranges. An alternative for non-variable stars is to add photographic spectrograms which will increase the signal-to-noise ratio by the square root of the number of plates provided there are no registration problems.

We are adding IIaO spectrograms obtained with the coude spectrograph of the 1.22-m (48-inch) telescope of the Dominion Astrophysical Observatory (DAO) (Richardson 1968). The elements of this horizontal spectrograph are mechanically isolated from one another. This extremely stable instrument has been maintained so that two spectrograms of the same non-variable star taken many years apart, exposed to the same amount of starlight, and developed using the same procedures will resemble two such spectrograms taken on successive nights.

---

[1] Visiting Observer at the Dominion Astrophysical Observatory
[2] NRC-NASA Research Associate
[3] On leave from the Department of Physics, The Citadel, Charleston, SC 29409 USA

C. R. Cowley et al (eds.), Upper Main Sequence Stars with Anomalous Abundances, 209–215.

2. DAO REDUCTION PROCEDURES

The DAO reduction programs are designed to make the reduction of photographic spectrograms as simple as possible without sacrificing accuracy and precision. The properties of each spectrograph are employed as early as possible in the reduction and scanning procedure. For a given camera and grating rotation except for minor differences, the location of clear plate, the comparison lines, the calibration steps, and the spectrum have the same relative positions on all exposures. Most of the time at the PDS microdensitometer is spent preparing to trace plates: aligning and focusing them and then entering commands for SCANN (Fisher, Morris, and Hoffman 1983), the DAO PDS spectrum scanning program. The use of lenses with a reasonably large depth of field allows one to usually obtain a good focus over the entire plate. One can attain with the reduction procedures positional accuracies comparable with those attained by standard measuring devices. Experimentally there are no systematic differences in the zero points between stellar and comparison spectrum positions.

The default values of various parameters needed to scan plates are contained on disk. Any small changes needed to properly scan a given plate are quickly made. The step calibrations are first scanned at two or more standard wavelengths. The PDS scans from standard initial reference positions to remove the difficulty of identifying the weakest step. Then cuts are made with respect to a known reference wavelength λ_o located near the center of the plate through the clear plate, through both the upper and lower comparison spectra, and through the stellar spectrum. The PDS Autolok system keeps the stage within one micron of the desired scan position at all times.

The output from SCANN is processed by the interactive spectrophotometric reduction program REDUCE (Hill, Fisher, and Poeckert 1982). Its uses VELMEAS (Hill, Ramsden, Fisher, and Morris 1982) to analyze arc spectra. A standard plate (X(mm) vs. λ(Å)) calculated with known spectrographic parameters and a list of arc wavelengths is used to predict the line positions. This method is very efficient as it uses differential measurements made with respect to known arc positions. Two cursor placements (line center and wing) for each line are made at a graphics terminal. Corrections are applied to predict the position of each new line. When the corrections have become sufficiently small, one can switch to an automatic mode. After the arc spectrum has been measured, a polynomial is fit through the data. One can accept the computed fit or adjust it manually.

The clear plate is scanned parallel to, but usually sampled less often than the stellar spectrum. One defines the number of points over which the clear values are to be averaged. The individual data and the averages are displayed on the screen. One can accept, alter, or delete any clear plate values. This clear plate file, converted to λ by the stored λ calibration from the comparison spectrum provides the zero point for calculating the densities.

The calibrations are converted to Baker densities Δ (see, e.g. Baker 1949, de Vaucouleurs 1968) which correlate almost linearly with

https://doi.org/10.1017/S0252921100091545 Published online by Cambridge University Press

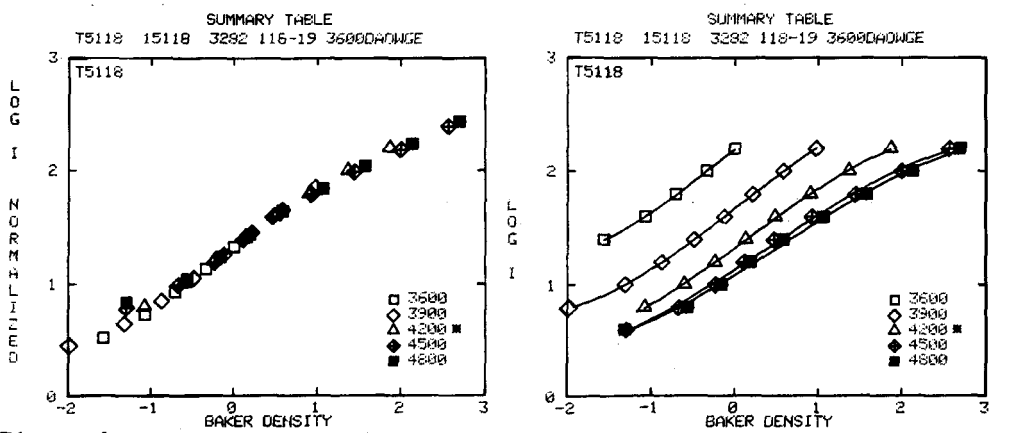

Figure 1. Log I vs. Baker density for five wavelengths for the DAO spectrogram 15118. a) shows the individual curves while b) the normalized curves.

log I. Baker density $\Delta = \log ((c/t)^{\gamma}-1)$ where t and c are microphotometer measures of the transmitted light through the spectrum and clear plate, respectively, and γ which varies from emulsion to emulsion is approximately 1. The data for each calibration wavelength are displayed together with the mean values for clear plate and each calibration step (see Figure 1). Bad values can be edited as appropriate. Once a calibration has been verified the process is repeated for the next calibration. After the final calibration has been processed all calibrations are displayed together for comparison. The data is next normalized to a previously identified reference λ and displayed, a procedure which indicates the validity of adopting a single calibration for the entire wavelength region.

To manipulate stellar files, they are linearized in equal λ (or $\ln\lambda$) steps. One does not want to greatly exceed the limits provided by extreme arc positions as polynomial extrapolation can be dangerous. The PDS densities are converted to intensity by using the reduced clear plate and calibration files. Radial velocity corrections are applied for the Earth's orbital velocity. As the calibrations are possibly wavelength dependent, they are linearly interpolated, but fixed over a small λ range (often 10Å) to reduce the number of calibrations. Possible difficulties with the stellar spectrum falling below the clear plate are displayed and adjustments to the clear plate can be made before the final intensity conversion.

The stellar intensity files are next rectified so that the continuum is unity to aid the measurement of equivalent widths and the cross-correlations of individual spectra. A continuum is fitted automatically by a combining the stellar data with a file of continuum λ's and λ intervals over which the averages must be taken. Interpolation with the program INTEP (Hill 1982a), which uses Hermite splines, among the averaged data completes the rectification. INTEP draws smooth stable curves through the continuum points without the oscillations often accompanying polynomial interpolation. The adopted continuum may be verified by stepping through the spectrum and

https://doi.org/10.1017/S0252921100091545 Published online by Cambridge University Press

comparing the continuum with the data. This is very important for sharp-lined stars as slight radial velocity differences can shift continuum values into line cores. The continuum averaging is controlled by a factor which allows this average to be based on all or part of the data within a specified interval. There is a strong psychological aversion to placing a continuum through the middle of a noise spectrum. It should be placed near there in spectral regions with few lines and somewhat higher in richer spectra.

The program VCROSS (Hill 1982b) is used to perform cross-correlations to obtain the relative radial velocity of one stellar spectrum with respect to another selected as a standard for coaddition. Conversion of the rectified stellar files into the $\ln\lambda$ format is made to aid the contrast of the cross-correlation. Spectral regions containing Balmer lines are excluded from this analysis. The Fourier transform of the program star spectrum is calculated with FOURT (Brenner 1970), then the conjugate transform of the reference star data and the product of these transforms is evaluated, which when appropriately normalized (see Simkin 1976) is the cross-correlation function. The peak of the c.c.f. is measured on a graphics terminal by delimiting a region and fitting a parabolic, a Gaussian, or a Lorentzian function to the data. The advantage of cross-correlation over more conventional techniques to measure relative radial velocities is that most of the stellar spectrum is used rather than just a small part.

The program TSTACK shifts the individual stellar rectified files to a common radial velocity by correcting for their relative radial velocities, interpolates the values to a grid of wavelength spacings, and then adds them. Then REDUCE is used to extract the profiles of strong lines, in particular Hγ and the He I lines, for comparison with the predictions of model atmospheres. The program VLINE (Hill, Fisher, and Poeckert 1982), which is now also a subroutine of REDUCE, and a faster version NEWVLINE were used to fit Gaussian, Lorentzian, and rotational profiles, as appropriate, through the stellar data (Figure 2). These programs are based on the curve-fitting routine CURFIT (Bevington 1969). Up to 12 profiles and a linear continuum of edited pieces of spectrum can be fit simultaneously to yield the line positions and widths and equivalent widths of the coadded data. Examination of the FWHM of the fits can reveal possible line blending. The reality of very weak features can be judged by their FWHM and line depths.

The following approximate numbers provide some feeling for the speed at which reductions proceed. With practice one can scan between 8 and 12 spectra on 2" x 8" plates in an hour on the PDS. By reducing arcs, calibrations, and clear plates, once can produce between 4 and 6 linearized intensity spectra per hour. Rectification of each spectra takes between 10 minutes and an hour depending on the complexity of the spectra and the wavelength region covered. Cross-correlation of ten rectified spectra takes less than 15 minutes (and can be done automatically). The coaddition process takes about 2 minutes. In flat regions, one can measure of order 100 features per hour: equivalent widths, positions, and v sini. In regions of Balmer lines,

https://doi.org/10.1017/S0252921100091545 Published online by Cambridge University Press

lam	err	EW(mA)	d	FWHM	Gaus N 38 vsini	Prof
4460.935	0.014	2.9	0.015	0.18	12	Gaus
4461.425	0.007	3.2	0.020	0.15	10	Gaus
4461.709	0.003	8.8	0.051	0.16	11	Gaus
4462.080	0.002	15.0	0.084	0.17	11	Gaus
4463.023	0.001	24.8	0.136	0.17	12	Gaus

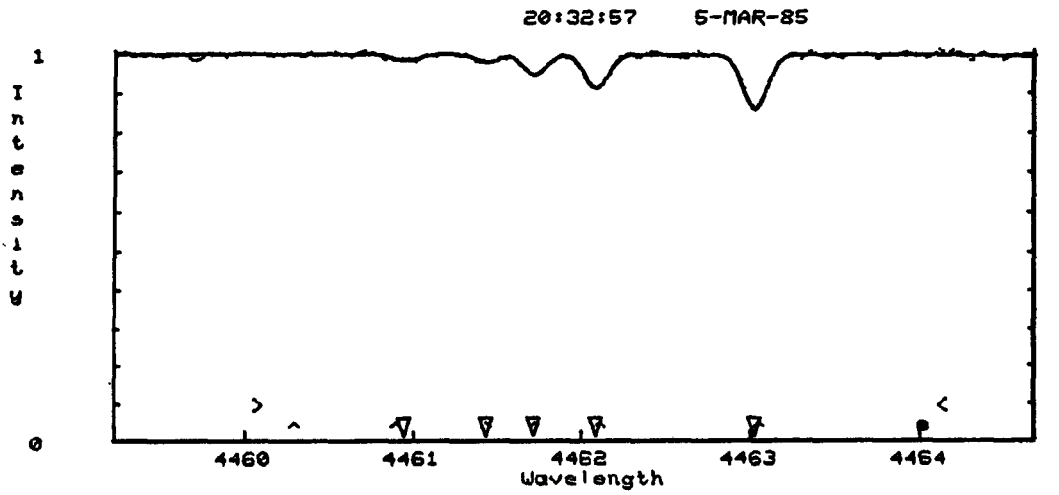

Figure 2. NEWVLINE measurements of the κ Cnc coadded spectra. The wavelengths, equivalent widths (in mÅ), the line depths (d), the FWHM (full width half maxima), and twice the v sini values are given.

the rate can be much slower. Obtaining values of the continua for the Hγ and He I line profiles takes 10 to 30 minutes. Many of these operations could be done faster if the graphics terminal worked faster (the current limitation at DAO is 9600 baud). To reduce the two halves of 2.4 Å/mm spectra of normal A stars takes about 3 to 4 days while for sharp-lined HgMn stars about twice as long is needed.

3. THE ANALYSIS PROGRAM

The combination of at least 6 similar spectrograms of the same star is an initial condition for our study. G. C. L. Aikman and C. R. Cowley have made available to us their DAO spectrograms of CP and normal stars. Our initial program stars, which are usually quite sharp-lined, for which we now have at least 6 2.4 IIaO Å/mm spectrograms include the normal stars τ Her, α Dra, and θ Leo and the HgMn stars μ Lep, ν Cnc, κ Cnc, ι CrB, υ Her, φ Her, and 28 Her. These stars include some previously analyzed by SJA using primarily Mt. Wilson Observatory 4.3 Å/mm IIaO spectrograms. This overlap will allow comparison of techniques and spectrographs as well as permit an initial comparison with 16 consistently analyzed sharp-lined B and A stars (Adelman 1985). As the DAO material for the stars in common consists of a larger number of spectrograms taken at higher dispersion

https://doi.org/10.1017/S0252921100091545 Published online by Cambridge University Press

and as the widths of the spectrograms are similar, we anticipate that the DAO material will have a higher signal-to-noise ratio than the Mt. Wilson material.

This material will be used to derive elemental abundances over a wide segment of the periodic table. Where possible resonance and/or low excitation line results will be compared with those of higher excitation lines. Searches will be made for evidence of atmospheric stratification and/or departures from LTE especially in the CP stars. Ultimately some of these derived abundances should provide critical tests of the radiative diffusion models for the production of the abundance anomalies. Ultraviolet analyses of the same stars should both complement and supplement this study (i.e. that of θ Leo, ι CrB, and κ Cnc by SJA and D. S. Leckrone with coadded IUE high dispersion images and planned Hubble Space Telescope observations by Leckrone). In addition, the relative radial velocities of the spectrograms, needed to coadd the spectrograms of a given star, will yield information on its binarity, furthering studies such as those of Aikman (1976). We also plan a stellar atlas as part of our line identification studies.

4. INITIAL RESULTS

Coadditions of 2.4 Å/mm IIaO spectrograms have been completed for the normal A star α Dra (6 plates) and the HgMn stars ι CrB and κ Cnc (10 plates each). The metal line profiles of α Dra are best fit in REDUCE with a rotational profile and those of ι CrB and κ Cnc by Gaussian profiles. Corrections for the instrumental profile (Fletcher et al. 1980) results in 12 km s^{-1} for α Dra, 3 km s^{-1} for ι CrB, and 5 km s^{-1} for κ Cnc. These values compare favorably with those in the literature: Slettebak et al. (1975) 15 km s^{-1} for α Dra, Wolff and Preston (1978) ≤3 and 6 km s^{-1} for ι CrB and κ Cnc, respectively, and Guthrie (1984) 6 km s^{-1} for κ Cnc.

Comparison of the Hγ profiles derived from the coadditions and spectrophotometry (Adelman 1978, Adelman and Pyper 1979) with the predictions of Kurucz's (1979) solar composition model atmospheres yield the following results:

α Dra T_{eff} = 10000 K, log g = 3.3
ι CrB T_{eff} = 10950 K, log g = 3.7
κ Cnc T_{eff} = 13250 K, log g = 3.5.

Corrections for a small amount of scattered light, 3-4%, (Fletcher, private communication) will improve the fit of the model predictions, which now match the line shoulders and wings.

For κ Cnc, the equivalent widths are systematically smaller than those of Aller (1970) in accord with both Heacox (1979) and Guthrie (1984). Compared with Aller (1970) who used similar dispersion spectrograms, many more lines, especially weak lines are seen, and new atomic species have been identified, e.g., S II, V II, and Y II.

We measured four lines on the ten rectified spectra of ι CrB. There is excellent agreement between the mean and coadded values. The formal 1σ (rms) values indicate errors of about 4 mÅ on single spectrograms, part of which is simply differences in the continuum

https://doi.org/10.1017/S0252921100091545 Published online by Cambridge University Press

placement.

	W_λ(mÅ)	
λ	coadd	individual spectra
4029.395	18.0	18.0 ± 3.7
4030.077	7.9	8.2 ± 3.6
4030.203	6.7	7.1 ± 3.0
4030.472	25.5	25.4 ± 3.7

Differences in equivalent widths by making slightly different choices of continuum placement with REDUCE are typically about $^1/_2$ mÅ in flat spectral regions in the coadded spectra. This suggests that very weak lines can be measured with some confidence.

ACKNOWLEDGMENTS. We appreciate the assistance of Wesley A. Fisher for his support of this research. This research has been supported in part by a grant from The Citadel Development Foundation to SJA.

REFERENCES

Adelman, S. J. 1978, Astrophys. J. 222, 547
Adelman, S. J. 1985, in preparation
Adelman, S. J., and Pyper, D. M. 1979, Astr. J. 84, 1603
Aikman, G. C. L. 1976, Pub. Dom. Astrophys. Obs. 14, 379
Aller, M. F. 1970, Astr. Astrophys. 6, 67
Baker, A. E. 1949, Pub. R. Obs. Edinburgh 1, 15
Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences (McGraw-Hill: New York)
Brenner, N. M. 1970, "FOURT"; available COSMIC/SHARE, Univ. of Georgia, Barrow Hall, Athens, Georgia
Cowley, C. R., and Adelman, S. J. 1983, Quar. J. Roy. Astr. Soc. 24, 393
de Vaucouleurs, G. 1968, Appl. Optics 7, 1513
Fletcher, J. M., Harmer, C. F. W., and Harmer, D. L. 1980, Pub. Dom. Astrophys. Obs. 15, 405
Fisher, W., Morris, S., and Hoffman, W. 1983, Pub. Dom. Astrophys. Obs. 16, 131
Guthrie, B. N. G. 1984, Mon. Not. Roy. Astr. Soc. 206, 85
Heacock, W. D. 1979, Astrophys. J. Suppl. 41, 675
Hill, G. 1982a, Pub. Dom. Astrophys. Obs. 16, 67
Hill, G. 1982b, Pub. Dom. Astrophys. Obs. 16, 59
Hill, G., Fisher, W. A., and Poeckert, R. 1982, Pub. Dom. Astrophys. Obs. 16, 43
Hill, G., Ramsden, D., Fisher, W. A., and Morris, S. C. 1982, Pub. Dom. Astrophys. Obs. 16, 11
Kurucz, R. L. 1979, Astrophys. J. Suppl. 40, 1
Richardson, E. H. 1968, J. Roy. Astr. Soc. Canada 62, 313
Simkin, S. M. 1974, Astr. Astrophys. 31, 129
Slettebak, A., Collins, G. W., Boyce, P. B., White, N. M., and Parkinson, T. C. 1975, Astrophys. J. Suppl. 29, 137
Wolff, S. C., and Preston, G. W. 1978, Astrophys. J. Suppl. 37, 371