MEASUREMENT OF LINE PROFILES

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ABSTRACT. The basic requirements for high precision spectral line profile measurements are reviewed, with the observatory at the University of Western Ontario serving to illustrate several of the points.

1. ADVANTAGES OF SMALL TELESCOPES

While there is some risk of repeating what has already been said at this meeting, I list here some of the advantages of using a small telescope:

* More observing time, and on a continuous basis, is often available. This is particularly important for stars showing time variablity, e.g., H and K emission or Zeeman broadening, or for projects requiring a large sample of objects.

* You can afford to make repeated observations to thoroughly establish calibrations and equipment stability, and verify astrophysical results.

* Equipment in the testing-debugging stage can often be left in place (Need not be removed for other observers).

* Facilities are usually easier to get to (observing can be integrated into your normal life) and to operate (I usually observe alone).

* Less support staff is needed. This makes for less expense and simpler coordination of activities.

* A breakdown does not automatically mean the loss of your observing run and the end of your observing for another year. When a breakdown does occur, you are on home territory with all your usual tools and test equipment. Other users of the telescope are close at hand and informal switching of the observing schedule can salvage most of the observing time.

* Justification of your observing plans is often minimal

J. B. Hearnshaw and P. L. Cottrell (eds.), Instrumentation and Research Programmes for Small Telescopes, 401–412.

Also notice that the intrinsic accuracy of measurement is not decreased because of small telescope aperture; observations will simply be limited to brighter stars. In fact, greater accuracy may be possible because a person has more time at the telescope to tune his equipment.

2. LINE PROFILE MEASUREMENTS

In this hour, we concentrate on some aspects of measuring line profiles. The widths of spectral lines vary systematically across the HR diagram and are controlled mainly by rotation and turbulence (very strong lines such as the Balmer lines excepted). Since Doppler broadening is often what we deal with, resolution is best specified in velocity units. For many F, G, and K stars, resolution of 2-4 km/s is adequate for measuring line profiles. For late-G and K dwarfs, somewhat higher resolution is desirable because the lines are very narrow. In early-type stars, rotation often produces very broad lines, in which case even modest spectral resolution will resolve the lines. In what follows, I shall concentrate on line profiles in the spectra of the late-type stars.

3. THE SPECTROGRAPH

Attaining high spectral resolution basically hinges on the diffraction grating, and not the size of the telescope. Choose a grating large enough to satisfy two constraints,

1) the diffraction pattern of the grating, of characteristic width W/λ radians, where W is the width of the grating, must map into a wavelength interval less than the desired resolution, and

2) no light should be lost by overfilling the grating.

For a fixed spectral resolution, point 2) actually amounts to an upper limit on the entrance slit width, W', set by the size of the grating. Upper limits on W' are undesirable because it means light will be lost at the entrance slit, a particularly nasty loss when working with a small telescope. The situation is easily understood in terms of the following equation:

$$\Delta\lambda = \frac{-\cos\alpha}{f_{coll}} \frac{d}{n} W' \qquad (1)$$

where $\Delta\lambda$ is the projection of W' into the spectral plane (equal to the spectral resolution in most cases), α is the angle of incidence onto the grating, d is the spacing between rulings, n the order in which the grating is used, and f_{coll} is the focal length of the collimator. One makes f_{coll} as long as possible in order to make W' appear angularly small. "As long as possible" in this case is determined by the f-ratio of the divergent telescope beam as it passes from the slit to the collimator, coupled with the grating size.

In practice, one buys the largest grating available, makes f_{coll} just long enough to fully fill the grating, and then the slit width must be set to give the desired $\Delta\lambda$ in equation (1).

Obviously, from equation (1), we also choose the grating to have d/n as small as possible.

Choice of camera depends basically on the detector. One sets the camera focal length, f_{cam}, such that $\Delta\lambda$ from equation (1) corresponds to two pixels. If f_{cam} is shorter, the spectrum will not have the measured points close enough together to get all the information. If f_{cam} is longer, the light will be spread out unnecessarily and exposure times will be correspondingly longer. The wavelength interval recorded also varies inversely with f_{cam}, so too long a focal length causes a double loss.

4. DETECTORS

There is not much point in using photography for modern high resolution spectroscopy. Differences in line profile shapes of a fraction of one per cent need to be measured, and photography can reach this level of precision only with great difficulty, if at all.

Electrical detectors have a signal-to-noise ratio given approximately (assuming Gaussian error distributions) by

$$S/N = \frac{n}{\sqrt{n + r^2}} \tag{2}$$

where n is the number of detected photons and r is the electronic noise of the system. When $r \ll n$, we have $S/N \sim \sqrt{n}$, and in principle the precision is limited only by the time available for collecting photons. A number of currently available detectors, such as Reticons and CCD's, have a significantly large r. When $r \gg n$, the detector is usually operating in an integrating mode, and $S/N \sim n/r$. The size of r in this case is critical. Typical values of r range from ~ 500 photons for Reticons down to ~ 50 photons for CCD's. Apparently the CCD would gain a factor ~ 10 in exposure time over a Reticon, and even lower r's for CCD's are expected in the near future, but this gain is only for relatively low S/N. In the current context, we need high S/N, hence large n, and the transition is made to the case where S/N varies as $\sqrt{n}$. In effect, r determines where this transition occurs. The actual gain from reduced r is somewhat less than expected at first glance (Fig. 1). For example, from Fig.1, at a S/N of 40, the CCD gains a factor of 7, but at S/N of 500, the CCD gain is only a factor of 1.6. Furthermore, if the net quantum efficiency of the CCD is a factor of two or three less than for the Reticon, as is often the case, then n is reduced by this same factor with a corresponding reduction in S/N. For the example in Fig. 1, the Reticon has the advantage for S/N > 200. As a rule of thumb, r is the more important factor for low S/N, while quantum efficiency is the more important factor for high S/N.

There are other factors that limit the ultimate signal-to-noise ratio attainable, such as the total number of charges that can reside on a pixel (< 1 E 5, or S/N < 300, for currently available CCD's, while for Reticons it is ~ 2 E 7, or S/N ~ 4500) and the inability to fully remove pixel-to-pixel sensitivity differences.

https://doi.org/10.1017/S0074180900151782 Published online by Cambridge University Press

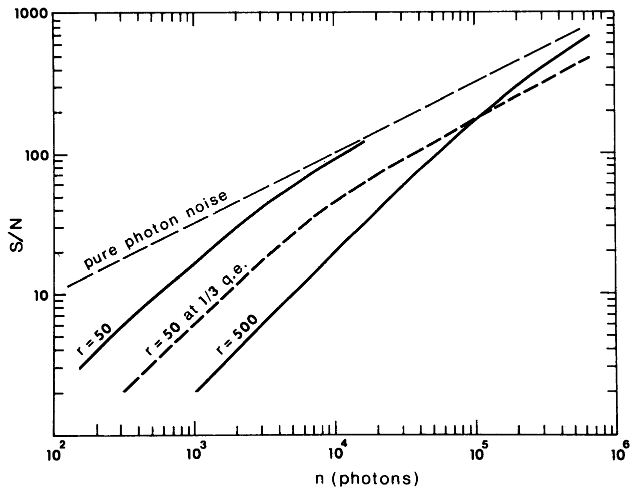

Fig. 1. Signal-to-noise ratio is shown vs. the number of photons incident on the detector, according to equation (2). A quantum efficiency of 1.0 was chosen for the two solid curves; a value of 1/3 for the shorter dashed curve, as labeled. Readout noise, r, is listed. At low S/N, r is the more important factor, but quantum efficiency is the more important factor for high S/N.

5. EXPOSURE TIME DETAILS

Exposure times for a fixed S/N can be reduced by increasing the optical throughput of the system. Frequent resurfacing of mirrors is advantageous. Better still is to use super-reflecting surfaces. An extra factor of two can easily be lost on a coude optical train if care is not exercised. Grating efficiency is also important in this regard. And high order gratings (echelles) can be annoying to use because the blazing has so many "off-blaze" portions across the spectrum. Image slicers should be used for cases where the stellar seeing disk is significantly larger than the entrance slit (and if it is not, beware of the stellar image itself acting as an entrance slit--and a moveable one at that). The image slicer can also result in more efficient photon delivery inside the spectrograph, as I will explain below.

There are problems associated with long exposure times, and since longer exposures might be correlated with smaller telescope aperture, they should be considered here. But an observer with even modest experience will be on the lookout for thermal leakage, slow electrical drifts inherent in silicon-diode detectors, and the presence of background skylight. I will, therefore, discuss only one item which I feel has not received sufficient attention, and that is the line broadening introduced by the diurnal rotation of the Earth. Simply stated, the radial component of the Earth's rotation changes during the exposure and "trails" the spectrum in the direction of dispersion. For a star of declination δ, at an hour angle t, being observed from a latitude ϕ, the elementary equation is $v = 0.465 \cos \delta \sin t \cos \phi$. Spurious broadening from diurnal radial velocity shifts is obviously limited to < 0.93 km/s, but since currently attainable measuring errors for line width parameters are ~ 0.1 km/s, even something much less than this upper bound can be an important systematic error.

Furthermore, it is easy to see that v changes most rapidly when the star is crossing the meridian, which is where all good observers strive

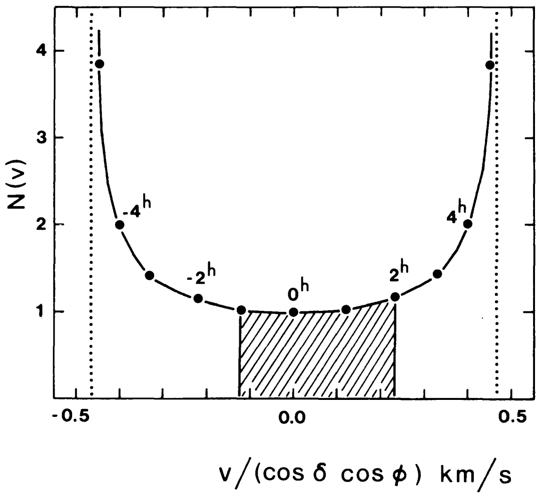

Fig. 2. The distribution of diurnal radial velocity is shown for 0° declination and 0° latitude. Integral hour angles are shown by the dots. A δ-function spectral line would have the shape of the solid curve (turned over if in absorption) for a star observed from horizon to horizon. The shaded region shows the broadening for a three hour exposure extending from -1^{h} to $+2^{h}$ in hour angle. The width amounts to 0.35 km/s.

to catch their program stars. The actual blurring introduced into the line profile will be the convolution of the instantaneously recorded profile with a segement of the distribution of v. Since dv/dt goes as cos t, the distribution of v, N(v), goes as 1/(cos t). For example, a star on the equator, observed from a low latitude observatory from 1 before meridian crossing to 2 after, will have v ranging from -0.12 km/s to +0.23 km/s, as shown in Fig. 2. A systematic error in line width of 0.35 km/s is certainly not negligible, and yet, I have never heard of anyone correcting for this important phenomenon.

6. LINE PROFILE MEASUREMENTS AT THE UWO OBSERVATORY

The 1.2 m telescope at the University of Western Ontario is about 25 km north of the campus (Fig. 3). Our horizontal coude room is vastly less burdensome on the taxpayer than one built to the 43° latitude slant (Fig. 4). The extra mirror needed to bring the light beam horizontal is supercoated for a broad spectral band and introduces a loss of 5%. The concrete floor acts as an optical table. It was laid on undisturbed subsoil and is physically isolated from the walls. The walls and ceiling are constructed of heavy concrete to provide a large thermal balast. Out side of the concrete is insulation and a double metal cladding. Typical temperature changes are as low as 1°C/week. Room lights and body heat introduce the largest thermal changes. The biggest air leakage occurs through the electrical outlets (on windy days).

The 200 μm wide entrance slit is part of a Richardson image slicer (Richardson 1966 P.A.S.P. 78, 436, Fig. 5). The effective entrance aperture of the slicer is 4".5 by 6".8. Four slices are used so that the rectangular shape of the grating is matched by the collimator beam. The collimator focal length is 6960 mm.

The Bausch and Lomb grating has 316 l/mm and a blaze angle of $63^{\circ}26'$. The visible spectrum is measured in the 15th through the 6th orders, and intermediate bandwidth interference filters are used to

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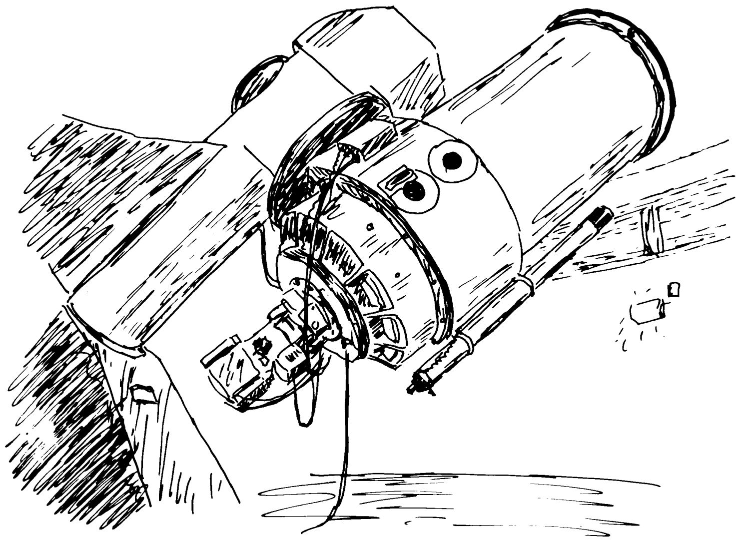

Fig. 3. The University of Western Ontario (U.W.O.) 1.2 m telescope was built by Boller and Chivens, Inc. and installed in 1969.

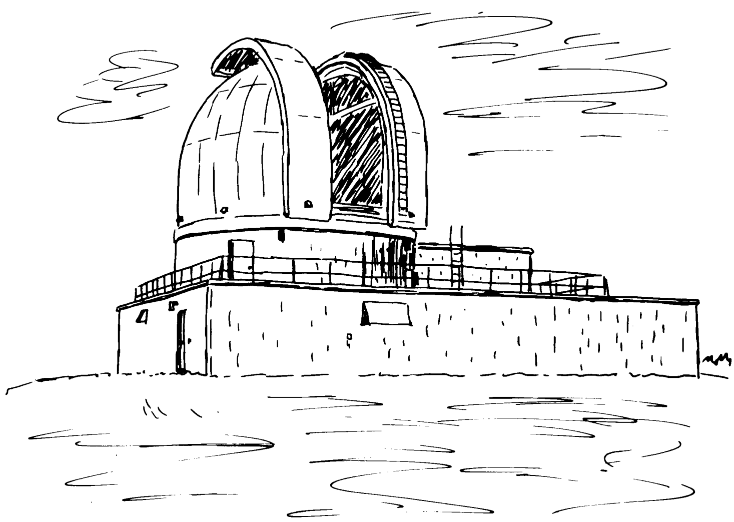

Fig. 4. The U.W.O. observatory is shown from the South. The horizontal coudé room can be seen as the extension of the building to the East.

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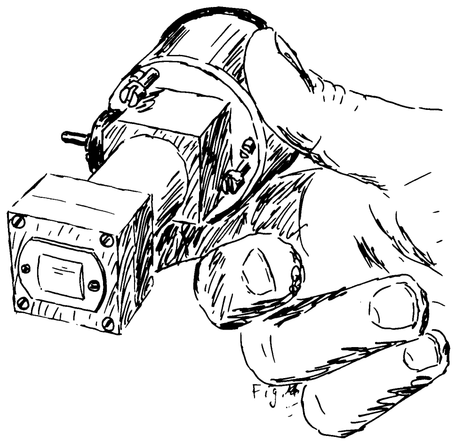

Fig. 5. This is a 4-slice Richardson image slicer. It comprises the entrance aperature to the coude spectrograph, and has an effective aperture of 4".5 by 6".8 on the sky. The optical throughput is more than double that of a simple slit.

isolate orders. These 25 mm diameter filters have peak transmission as high as 85%, and are somewhat more efficient than a cross-disperser for order sorting. Furthermore, the extra reflection from a cross-disperser is eliminated, so the orientation of the cameras need not be changed when switching between this quasi-echelle and conventional gratings working in lowest orders. The camera is a Schmidt, and a 45^{o} pick-off mirror is used to move the focus out of the optical beam. Two slices from the image slicer pass above the pick-off mirror (Fig. 6) and two pass below, resulting in no light being lost by this centrally located mirror. The focal length of the camera is 559 mm. The detector I have used in recent years is an 1872 diode Reticon. The individual diodes are 15 μm wide by 750 μm tall. Again, the image slicer is arranged to make the spectrum 750 μm high.

At 6250 A, working in the 9th order, the dispersion is ~ 0.038

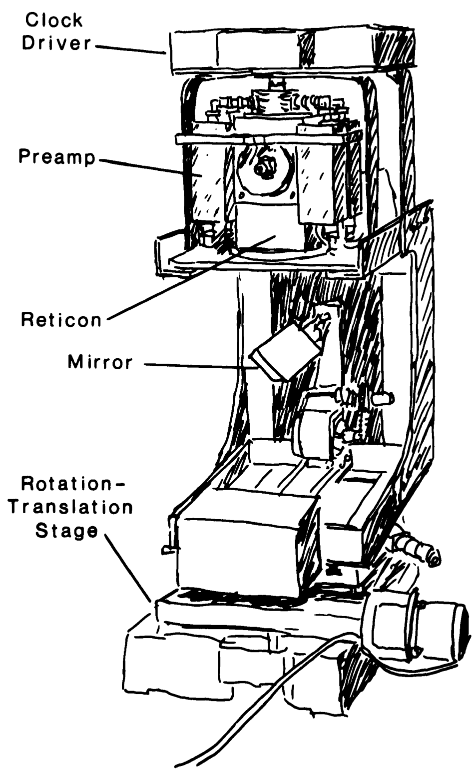

Fig. 6. This Reticon mount is inside the Schmidt camera. The light enters from the left, the spherical camera mirror is on the right (not shown). The focus is above the pick-off mirror on the Reticon inside the vacuum chamber. The whole assembly is mounted on a precision microscope stage used for optical alignment and microscanning.

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A/diode and the resolution is ~ 3.5 km/s. This system will attain a signal-to-noise ratio of 100 on a 6th magnitude star in one hour. Signal-to-noise ratios of several hundred are routinely used.

An example of stellar data is seen in Fig. 7. A number of startlingly weak features can be seen. Line blending at the 1% level is

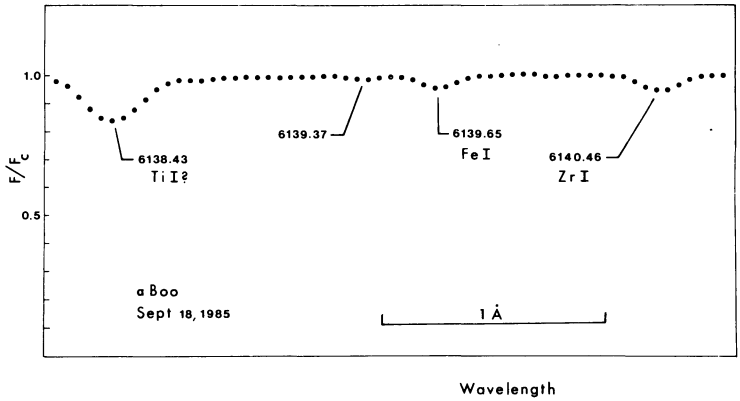

Fig. 7. A small portion of a typical exposure is shown here. A few lines are labeled; the two weakest ones are not.

obviously commonplace in cool stars. Only with high signal-to-noise data of this sort can we expect to measure line shapes and deduce interesting things about velocity fields in stellar atmospheres. The Fourier transform of a typical line shows that the "signal" information contained in the profile is adequately known, i.e., the Nyquist frequency, given by $\sigma_N = 1/(2\Delta\lambda)$, is high enough, or alternatively that $\Delta\lambda$ is small enough. In K dwarfs, the spectral lines become so narrow that finer sample spacing is desirable (Fig. 8). Microscanning is

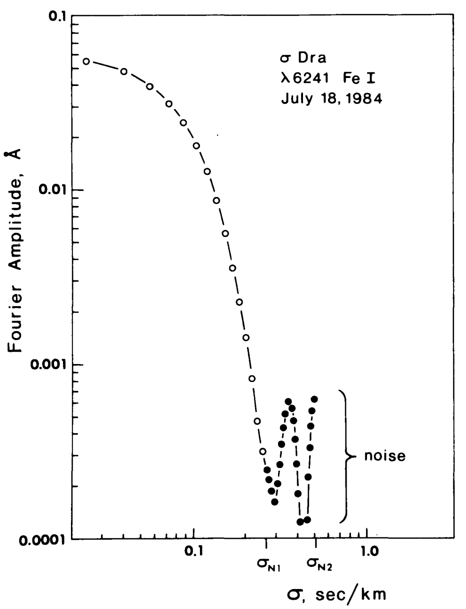

Fig. 8. The Fourier transform of λ6240.65 in σ Dra (K2 V) is shown for two data spacings. The first Nyquist frequency, σ_{N1}, corresponds to a single Reticon exposure with $\Delta\lambda$ = 0.037870 A between diodes. This data spacing is just adequate for line broadening analyses. The second Nyquist frequency, σ_{N2}, results when two exposures are interlaced.

introduced to alleviate this problem--two succesive exposures are taken with a half-diode shift introduced between them. The data numbers are then interlaced (Fig. 9). One example of the improvement from micro-scanning is seen in Fig. 10, where a line bisector is shown. A line bisector is a measure of a line's asymmetry, in this case caused by granulation on the stellar surface. (The shape of the bisector is not very sensitive to the spectral resolution, which remains unchanged.) I think you will agree that the bisector from the interlaced data is superior to those from the individual exposures alone.

You may wonder, since double the exposure time is needed to take the two successive exposures when microscanning, why the camera focal length is not simply made twice as long. That would give twice the density of measurements as required, and since the photons are spread out twice as much, the two exposures would be wrapped into a single one of twice the duration. One would save the (minor) effort of interlacing the two data sets. But microscanning has these advantages: 1) the field coverage is twice as large, and 2) microscanning is not used when it is not needed, so for most stars, the exposures are not doubled. (They would always be doubled if the longer camera focal length were used!) Another important detail is the double height spectrum that would result from doubling the camera focal length, i.e., half the light would be off the detector, and a cylindrical lens would have to be introduced in front of the Reticon to salvage part of it, or else the length of the entrance slit would have to be cut in half, reducing the optical throughput.

I have been please with the productivity of our coude installation at Western Ontario. Coude spectroscopy has many advantages over Cassegrain spectroscopy, especially when high resolution and high signal-to-noise data are basic requirements, but some Cassegrain work can also be done with a small telescope by using an echelle to get high angular dispersion. If you do not have a coude spectrograph, you might consider using a floor mounted echelle spectrograph fed by fiber optics from the Cassegrain focus.

7. EXAMPLES OF RESEARCH USING SPECTRAL LINE PROFILES

One can hardly guess at what the future might hold for high resolution spectroscopy, but here are some currently active research areas:

* velocity fields (turbulence)
* rotation (v sin i)

from line shape and broadening

* magnetic field measurments using Zeeman broadening
* starspot tracers--following bumps across line profiles
* stellar granulation measurements from asymmetries in lines
* radial oscillation in classical variable stars
* nonradial oscillations

from time series of profile or radial velocity changes

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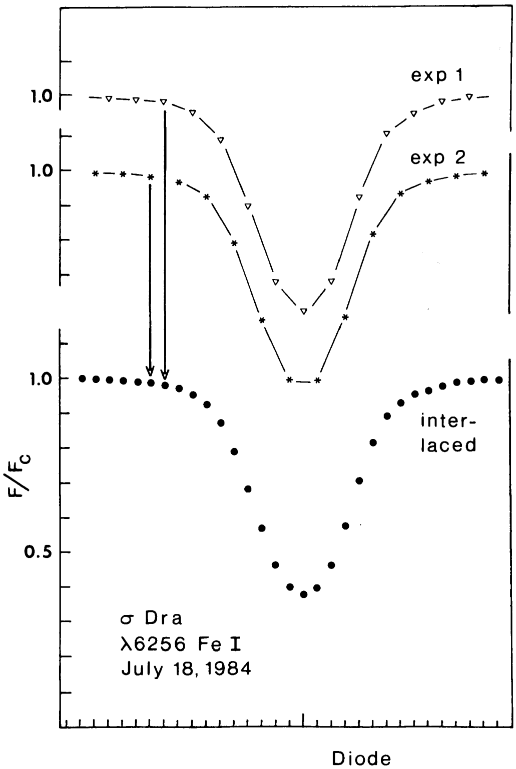

Fig. 9. Microscanning allows two succesive exposures to be interlaced to double the number of points on the profile. (The spectral resolution is not changed.) The topmost curve is from the first exposure; the next down from the second. The combined measurements are shown in the bottom-most profile. The array is moved half a diode width along the direction of dispersion by the precision microscope stage between exposures.

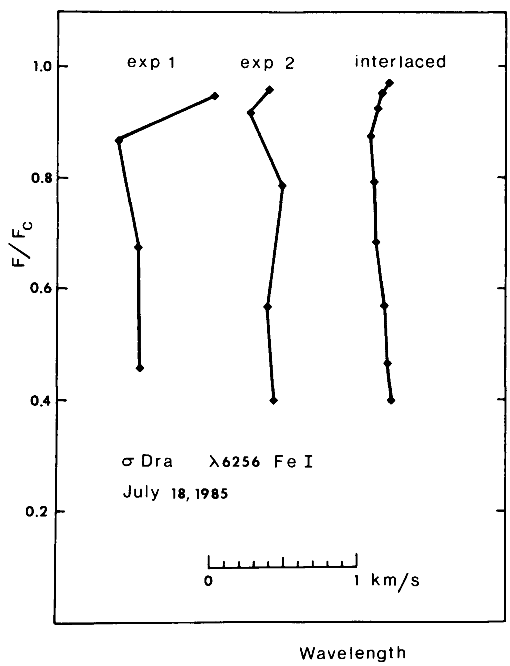

Fig. 10. Line bisectors, which show the asymmetry of the profile, are plotted for the three profiles of Fig. 9. Without microscanning, a narrow-lined star like this one does not give a sufficiently large number of points on the bisector causing them to be ill defined (left and center). The bisector on the right is for the same exposures interlaced. The "C" shape, so familiar in the solar lines, can be clearly seen.

* geometrical shapes of close binary system from the "rotation" profile

* Ca II H & K and H_α variability

Currently attainable signal-to-noise ratios of 100 to 1000 allow these phenomena to be studied. Spectral resolution better than ~ 5 km/s is needed, except for rotation measurements in earlier-type stars. Some wider lines, such as the Na D lines, the Ca II IR triplet, or Balmer lines could also be studied with somewhat lower spectral resolution. For the cooler dwarfs resolution of ~ 2 km/s is desirable.

The list above gives just some of possibilities, and you can expand it as needed to suit your own interests. At the same time, many of the listings are far from mature research topics, and there is still plenty of work to be done....

I am grateful to the Natural Sciences and Engineering Research Council of Canada for continuing financial support.

DISCUSSION

Gaustad: If the original spectrum is truly critically sampled, it should contain all the information possible, and a proper mathematical interpolation should provide any desired degree of fineness in the line profile. Therefore I don't understand the necessity for a repeated exposure to get interlaced data points.

Gray: First, you increase the signal-to-noise with the second exposure (by $\sqrt{2}$). Second, a simple 5-point interpolation will not give the true profile.

White: Have there been any advances beyond the Richardson and Bowen image slicers? I was thinking in terms of fibre optics.

Gray: The Richardson image slicer is impossible to improve upon. The Bowen one is not always in focus along the slit. In our system 2 slices go above the pick-off mirror and 2 go below it. Thus we don't lose any light on this mirror. The slicer changed the focal ratio from f/31 to f/41 which then fitted our grating.

Duncan: An appeal for additional observations. Some of the phenomena (e.g. rotation and chromospheric activity) associated with stars are time dependent. If one is trying to determine the ages of stars using these phenomena, there is a real lack of young stars of known age. Stromgren photometry is able to differentiate the older stars, 2-10 x 10^9 years, but there is a deficiency of stars with ages known to be < 10^9 years. One could find these stars as components of visual binaries. There are a lot of binaries known where the primary is an A or B star, which is young, but most of the secondaries don't have spectral types. We need some of these to be of later spectral type to calibrate with their time dependent phenomena.