THE BUYING POWER OF HIGH SIGNAL-TO-NOISE RATIOS IN SPECTROSCOPY

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ABSTRACT. High S/N is a good first step toward accurate profiles.

1. INTRODUCTION

I developed an interest in high S/N spectroscopy (S/N is used here for signal-to-noise ratio) in the early 1970's, and I built a photoelectric line scanner consisting of a photomultiplier behind an exit slit placed in the focal plane of a 13 meter focal-length camera. The slit and photomultiplier were marched repeatedly across the spectral line with about a minute of integration at each position. I can still remember spending a whole night measuring about 30 points across Na D lines of a fourth magnitude star and attaining the stupendous signal-to-noise ratio of 50! I'm not sure what gave us the faith to continue, except that we knew there was a great deal of untapped information in those line profiles. We can now measure the same star at about 2000 wavelength points with five times higher spectral resolution, and in one hour surpass a S/N of several hundred. With some effort, S/N ~ 1000 can apparently be achieved. I say apparently because the meaning of S/N varies with the application and because there is more to dependable line profile measurement than a low noise level, as I shall point out below. But lowering the noise level is a good start, allowing us to buy our way into whole new research endeavors.

2. INTERPLAY OF S/N AND RESOLUTION

In most line profile work, spectral resolution and S/N are related. Typical absorption line profiles are unimodal, and so differences in shape appear as "higher order" effects, which means that the differences appear toward higher Fourier frequencies. Figure 1 illustrates this. Both high S/N <u>and</u> high spectral resolution are needed to see the high frequency portions of these transforms.

The cool-faint portion of the HR diagram is populated by stars having the narrowest spectral lines. For K dwarfs, we need resolution of at least 2.5 km/s, but as the noise is pushed down, and the Fourier

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 185–191.

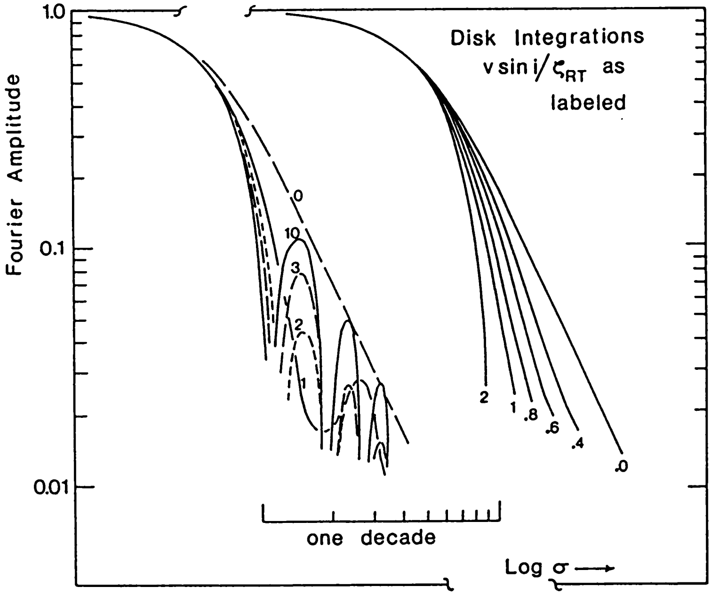

Fig. 1. Model disk integrations were used to combine the Doppler-shift distributions of rotation and radial-tangential macroturbulence. Their Fourier transforms are shown for various ratios of rotation to macroturbulence dispersion, ζ_{RT}. The differences are seen to be larger at higher Fourier frequencies where the amplitudes are smaller and (in the observations) closer to the noise level.

transforms are followed to ever higher frequencies, we may need even S/N higher resolution. Naturally we can expect exposure times to go up as we strive for higher S/N and higher resolution. With silicon-diode-type detectors, S/N improves linearly with exposure time initially because detector noise dominates, but eventually we cross into the photon-noise-dominated domain.

The cost of higher resolution depends on whether or not a good image slicer is used. Without a slicer, we pay at the entrance slit and at the detector, so the exposure increases as the square of the resolution. With a slicer, the exposure increases with the first power of the resolution. In both cases we loose field in proportion to the increase in resolution.

3. THE ROLE OF S/N IN LINE BROADENING ANALYSIS

The key to separating macroturbulence from rotation in F, G, and K stars is to be able to place the observations in a grid like the one shown in Figure 1. Unless we clearly see the transform of the stellar lines above the noise, we will be unsuccessful. In the case where rotation dominates (v sin i/ζ_{RT} > 2), the information on the size of the macroturbulence dispersion, ζ_{RT}, is contained almost exclusively in the sidelobe height (left side of Fig. 1). Most G and K stars have v sin i/ $\zeta_{RT} < 1$; then the right side of Figure 1 is relevant.

Fourier analysis has been applied to a significant number of stars in the F, G, and K portion of the HR diagram. A summary of the results for macroturbulence is given in Gray and Toner (1987). Simply stated, the macroturbulence dispersion increases monotonically with luminosity and effective temperature. It turns out that uncertainty in the luminosity classification is a significant source of scatter in this diagram, and it may be that the size of ζ_{RT} is a more sensitive measure of luminosity than the standard classification methods.

Some recent observations of σ Dra (K0 V) are shown in Figure 2. I have combined a number of separate exposures to force the noise level down. Each successive step toward the right in the diagram includes more data, and as the S/N pushes past ~ 500, one begins to see the sidelobe emerge. This sidelobe arises from the onset of saturation in the line profile and so it is sensitive to desaturation mechanisms such as microturbulence.

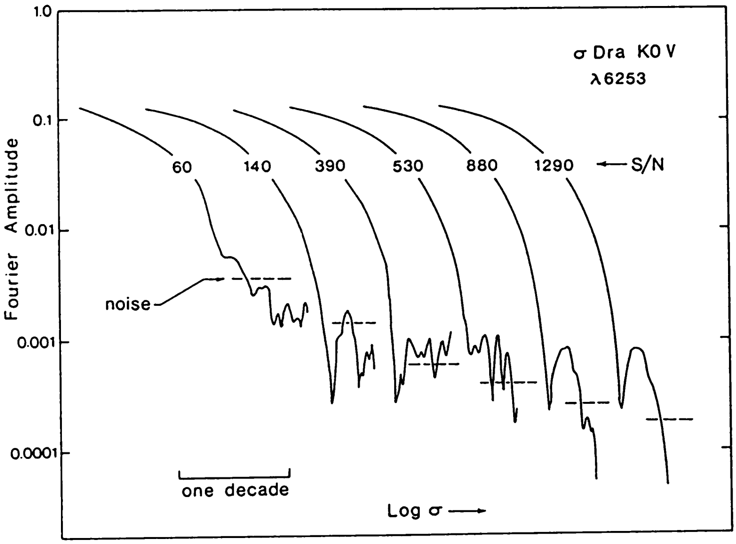

Fig. 2. The Fourier transform of Fe I λ6252.57 is shown for various S/N values in the continuum of the spectrum. A weak sidelobe appears for the highest S/N cases toward the right.

Currently attainable S/N is already sufficient to show up weak points in the kinematic modeling. In some instances, ζ_{RT} seems to be a function of depth (Gray 1982b), and this is not included in the usual modeling. Further, real stellar line profiles are rarely if ever symmetric, but the line shape analyses usually ignore this important aspect for sake of tractability. But let us turn our attention to it now.

4. THE ROLE OF S/N IN STELLAR GRANULATION MEASUREMENTS

The signature of stellar granulation is the asymmetry seen in the spectral lines. Most commonly this is displayed using the line bisector (see Dravins et al. 1981, Gray 1982a). In a typical solar bisector, the rising hot granules produce a blue shift in the main portion of the line because they dominate the light. The cooler, less bright, falling material produces a positive tail on the overall velocity distribution, and this is seen as a depression of the red wing of the profile which in turn produces a redward bend in the top of the bisector. In the sun, the granulation contrast has largely disappeared at the higher layers where the line cores are formed, and so the blue shift does not occur in the lower part of the bisectors of strong lines. The net effect is C-shaped bisectors. Stars hotter and more luminous than the sun show blue shifts even in the line cores, so we know that granulation penetrates higher in their photospheres than for the solar case.

Elementary considerations tell us that our ability to measure bisectors depends on the S/N in the profile coupled with the slope of the profile. A given photometric error translates into a larger velocity error in the wings and core of the line (Gray 1984). Midway down a strong line, the slope might be ~ 10% per km/sec, leading to expected bisector errors ~ 70 m/sec for S/N of 100. Since a typical bisector has a span of only ~ 100 m/sec, we clearly need S/N in excess of 100.

Interestingly, the importance of spectral resolution on the bisectors is very different from that of profile-shape analysis. Instead of a continuous interplay between S/N and resolution, here we have a semi-binary situation: the exact resolving power is not very important as long as it is in excess of about 100,000. This comes about because the bisectors themselves do not have high Fourier components, making really high resolution unnecessary, while resolving power < 50000 results in smearing over a significant fraction of the profile, wiping out the asymmetry of the line. A number of observational experiments along this line have been done by Dravins (1987).

Even with the modest S/N of a few hundred, we have been able to show that granulation is stronger and penetrates higher into the stellar photosphere as the luminosity and/or the effective temperature increases. One uncertain part of this overall behavior was for the K dwarfs, where there was some indication of deviation from a monotonic trend (Gray 1982b). In Figures 3, I show some more intensive studies on dwarfs. The main improvement here over former studies is in pushing the S/N from ~ 100-300 to ~ 1000. We see in the figure the C shape so typical of solar bisectors, and we see a very small velocity span, ~ 100 m/s, also typical of the solar case. Dravins (1987) has found similar results for α Cen A (G2 V) and B (K1 V). So it now appears that there is indeed a general decrease in the vigor of granulation toward the lower right portion of the HR diagram, consistent with the behavior of macroturbulence dispersion.

Toward hotter stars, an interesting reversal of the classical cool-star line asymmetry occurs. The behavior is rather striking in Ib supergiants (Gray and Toner 1986). Some important atmospheric changes are taking place as a star evolves across the HR diagram.

One interesting need for ultra-high S/N in line asymmetry work is with the "rotation effect." Simple numerical simulations (Gray and Toner 1985) predicted bisector displacements enhanced by rotation, and I have attempted to use this effect to pin down actual granule rise velocities (Gray 1986a). Previously we had thought that absolute velocity measurements for bisectors were impossible because of the arbitrary radial velocity of the star. But the Doppler-shift distribution, broadened by rotation, supplies the needed zero-velocity position. Rise velocities of 1.5 km/s seems to be typical of granules. The reason ultra-high S/N is of value here is because profiles broadened by rotation are very shallow--have small slopes which magnify the photometric errors into large bisector noise. So although the rotation effect may prove to be a useful tool for granulation studies, we will have to work diligently on improving the S/N if we hope to exploit it.

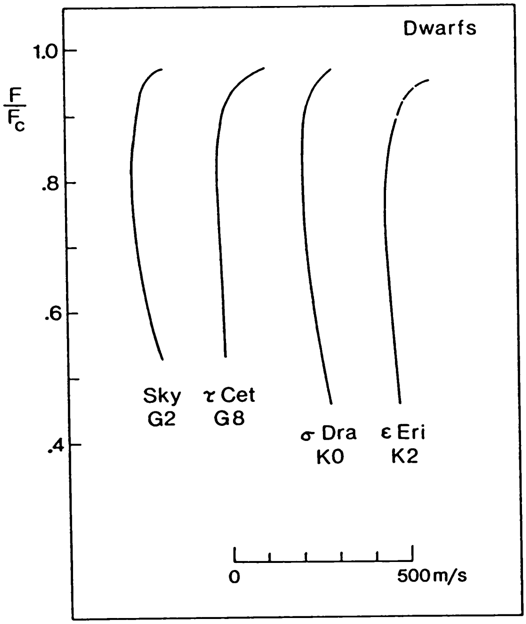

Fig. 3. Cool dwarfs do have C-shaped bisectors, as illustrated here. These bisectors are means of several lines and many exposures. Notice that the characteristic velocity span is ~ 100 m/s.

5. BEYOND HIGH S/N

High S/N is just the first step on a much more comprehensive buying plan. It has given us buying power to study turbulence, rotation, granulation, magnetic fields, starspots...., but it will not be long before we will have to face up to other limitations to accurate spectroscopic measurements. Among these are:

1) line blending - it varies markedly with spectral type and with spectral region, but always becomes more serious as S/N increases because then the more numerous weak blends make a difference instead of being buried in the noise.

2) instrumental profile - the only way uncertainty here could be completely eliminated is by making the instrumental profile very narrow compared to the stellar lines. This is feasible only for the sun. For other stars, we are photon starved and cannot afford the luxury of such a narrow instrumental profile. Problems arise because it is usually necessary to measure the instrumental profile at a grating setting different from that used when measuring the star; the polarization properties of the instrumental profile from image slicers, mirrors, filters, grating, and detector are probably significant but usually ignored.

3) scattered light - a difficult contamination to measure since it can vary with grating orientation, wavelength, and techniques of order sorting.

4) diurnal rotation of the earth - the projection of the earth's rotational velocity vector onto the direction of the star can vary enough during a long exposure to broaden the spectral lines by up to several tenths of a km/s (Gray 1986b).

5) detector stability and geometry - mechanical and thermal drifting can occur. At some level the irregularities of the pixel size and spacing introduce errors.

6) detector electrical flaws - modern detectors can have latent images, incomplete charge transfer, spurious clocking periodicities, etc.

7) nonlinear response - no detector is perfectly linear. Many show zero-point problems, or saturation effects, or integration errors. Interference fringing can also introduce a modulated response.

8) nonuniform illumination of optics - collimation errors and differences in illumination, especially of in-beam obstructions, for starlight, flat-field lamps, and instrumental profile lamps can cause distortions and various field errors.

Alas, the S/N can be very high and we still may not have data suitable for comparison with theory. Nevertheless, high S/N has given us the buying power to open up the "new" spectroscopy.

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DISCUSSION

SODERBLOM Can you tell us the name of the "friendly dwarf" please ?

GRAY Eventually, yes. But I am not at liberty to do so quite yet because a PhD thesis is involved.

PRADERIE You report a variation of 7% in equivalent width. What is then the accuracy on the measurement of W ?

GRAY Well, the apparent precision can be better than 0.25%.

BOHANNAN One thing that has become clearer to me during this symposium is that the buying power of reducing observations has to be considered when designing instrumentation and planning observing programs.

GRAY Sure.

EBBETS Your illustration of the interplay between signal to noise ratio and resolution might suggest that for a given resolution there is a maximum S/N that is worth obtaining. The higher Fourier frequencies are attenuated by the instrumental broadening. Isn't it true though that higher S/N allows you to detect and measure weaker and weaker lines, you just can't distinguish their shapes from that of the instrumental profile ?

GRAY You are quite right in the sense that lower and lower noise will not let us see any Fourier amplitudes that have been severely filtered by the instrumental profile transform. Then higher spectral resolution is the answer to such a situation.