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A Spectrograph's Instrumental Profile and Scattered Light

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Abstract. With the advent of high signal-to-noise detectors on high resolution spectrographs, new emphasis is being placed on two often ignored factors, the instrumental profile and scattered light. The general characteristics of both are reviewed and some specific examples are discussed. An unsuccessful attempt to determine the scattered light contribution by comparison of an FTS solar spectrum with a sky spectrum is described. Finally the comparison of the observed Hγ profile of Vega with a scanner profile is shown to produce satisfactory results.

1. Some General Observations

The instrumental profile of any spectrograph, which provides information about the degradation of an object's spectrum, is focus dependent. To get as narrow a profile as possible, one wants a well focused spectrograph. Most of the older spectrographs were designed for use with photographic plates, which were often bent in a plate holder so that the plate could follow the curved best focal surface. Many electronic detectors are flat devices. Thus to focus with them, one uses lines half way between the center and each edge. This results in a good focus as long as the detector is not too long. For longer CCDs, a field flattener might have to be used. Some recent CCDs have been bent to get better focusing characteristics.

The projected slit width, in meters, is order independent. So in the usual case when the instrumental profile is dominated by the slit width, it is basically order independent. Usually it is converted to a wavelength scale using the dispersion of the stellar spectrum at each point of interest. Ghosts, unfortunately, scale in strength as the square of the order and are due to periodic ruling errors. If a grating has more than one periodic error, then the interference of the differ-

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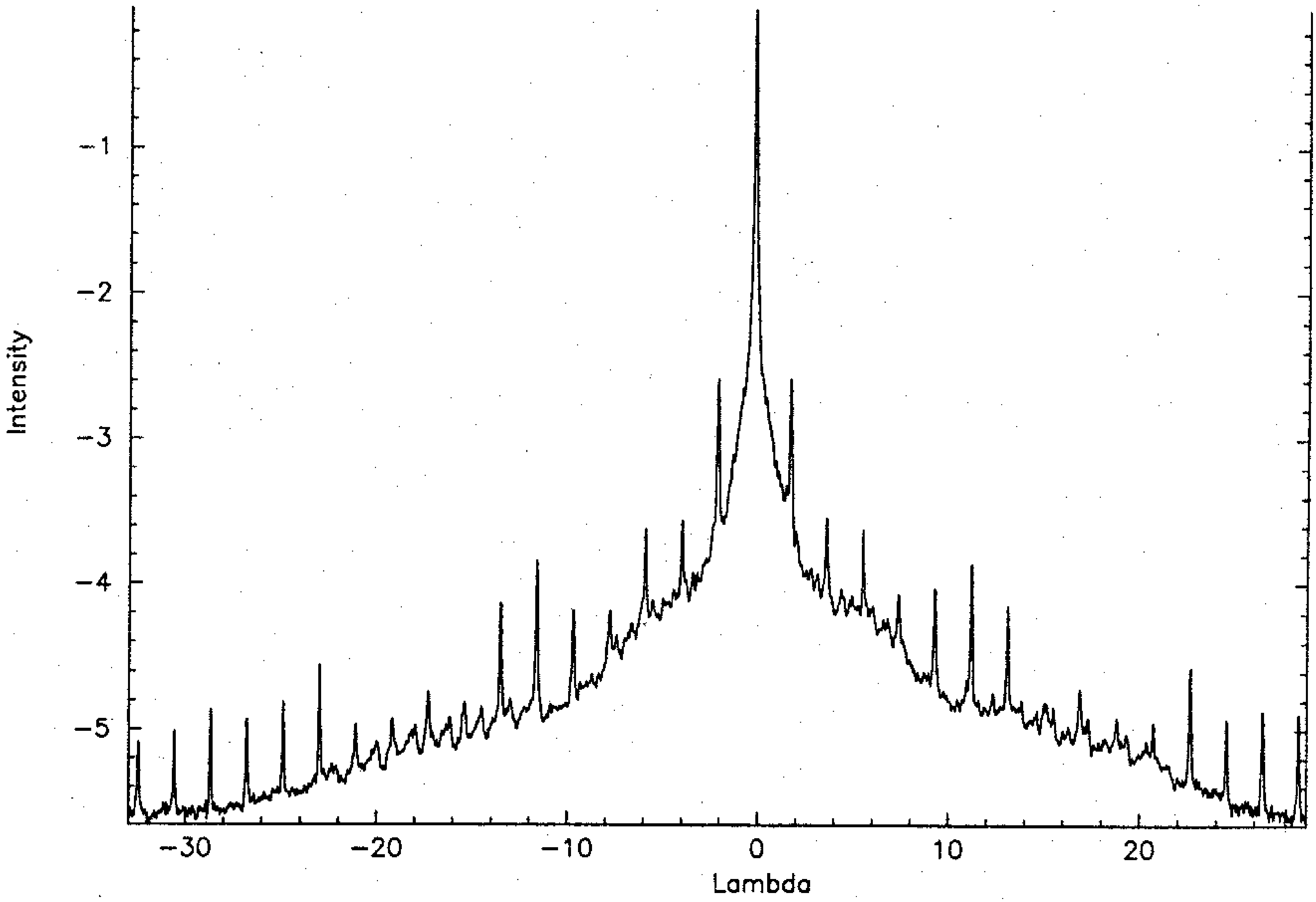

Figure 1. The laser illuminated, log intensity instrumental profile of Booth et al. (1990) for the 9682 DAO coudé spectrograph.

ent systems of ghosts can produce ghosts far from their parent lines. As a small wavelength dependence can be produced by the projection factor of the entrance slit and transmission optics, it is a good procedure to measure the instrumental profile at several different wavelengths and then model the differences for other wavelengths.

In a spectrograph, some of the incident photons at each wavelength do not go where the designer intended. Such scattered photons are produced by optical imperfections in the optical elements, dust in the air, and/or diffraction from some aperture in the instrument. Scattered light fills in absorption lines and thus produces systematic errors in the profile and a loss of contrast.

To properly account for scattered light, one needs to measure the instrumental profile in a wavelength interval which is comparable to the spectral bandpass of the system. For a wide bandpass system, this is not possible. Yet the cumulative effect of the very weak instrumental profile wings combined with the continuous spectrum of the star is significant. Canonically a classical coudé spectrograph with clean optical surfaces has scattered light whose intensity is about 4% (Fletcher 1990) of the continuum level. As the scattered light at a given point in the spectrum is an integral which involves the spectral responses of the instrument and detector, the transmission losses in the Earth's atmosphere, filter transmission (if any), the stellar flux, and possibly other factors, it is wavelength dependent. For example in stars with strong Balmer lines, the scattered light will be modulated by them.

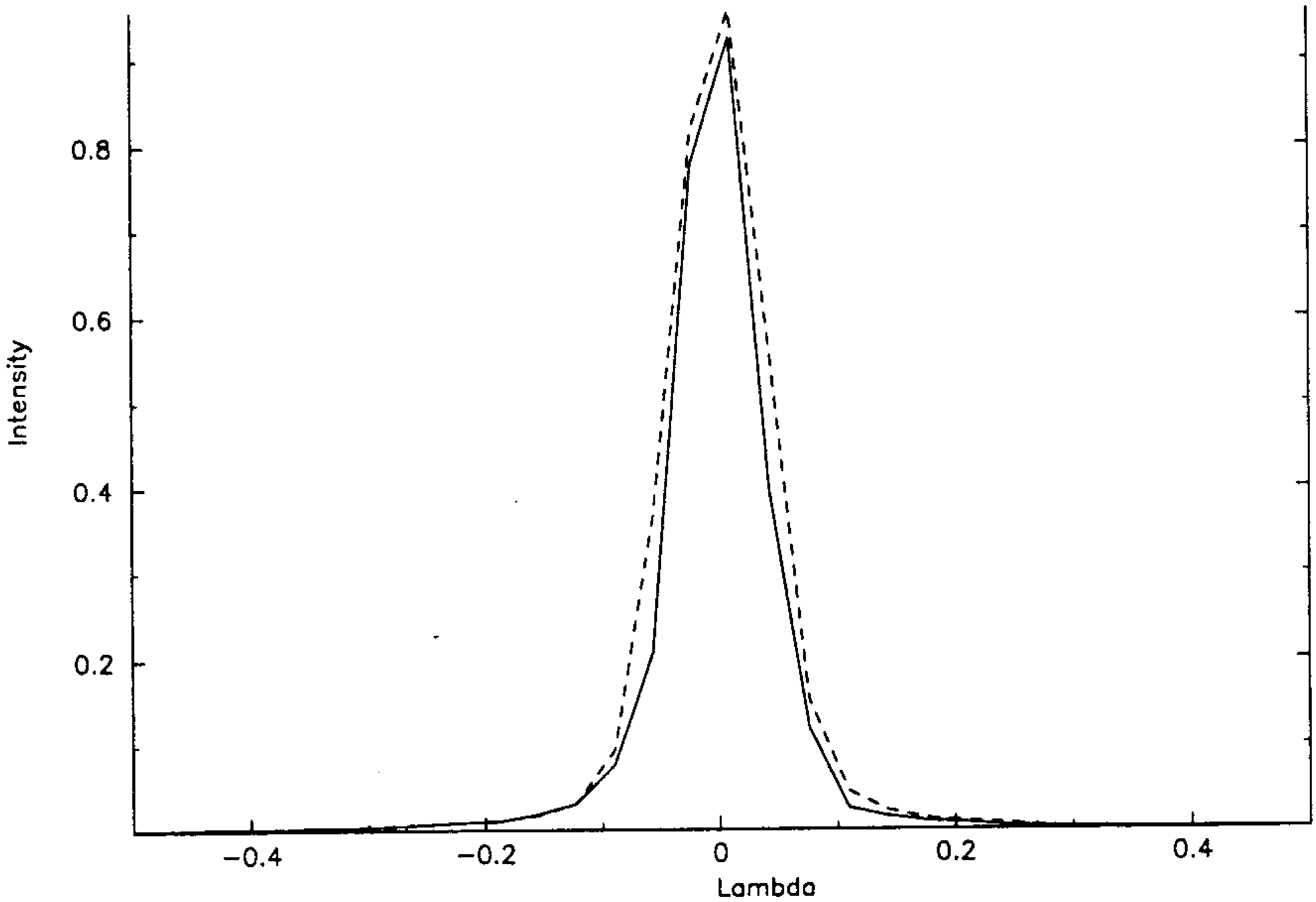

Figure 2. The central cores for the laser (solid line; Booth et al. 1990) and comparison spectrum (dashed line; Gulliver and Hill 1990) instrumental profiles.

The instrumental profile is usually measured using a source with intrinsically narrow lines. Examples include lasers, telluric absorption features, and hollow cathode lamps filled with a gas of a heavy element such as one of the isotopes of Hg or Th. These sources have intrinsic line widths much less than the instrumental profile. Often even Fe lines can be used.

Figure 1 shows an example of a He-Ne (6328 Å) laser illuminated instrumental profile determined by Booth et al. (1990) using a Reticon detector in the second order of the 800 lines mm^{-1}, 96-inch long camera of the DAO coudé spectrograph . Although a large number of ghosts are evident, these have never been directly detected in a stellar spectrum even at the ultra-high signal-to-noise (S/N) achieved for Vega (Gulliver et al. 1994). Before convolving the instrumental profile in Figure 1 with a spectrum, the profile must have equal red and blue extents.

A major problem is that one can only measure the line profile so far from the line center. With photographic plates the line quickly drops below the noise level. A classic study is that done by Griffin (1968) in his Arcturus Atlas for the coudé spectrograph at Mt. Wilson Observatory. With electronic detectors, one can go further from the line center, but when the detector approaches saturation in the emission line case, near line center, one has to stop the exposure if one wants to measure the central region. One might think that one might be able to

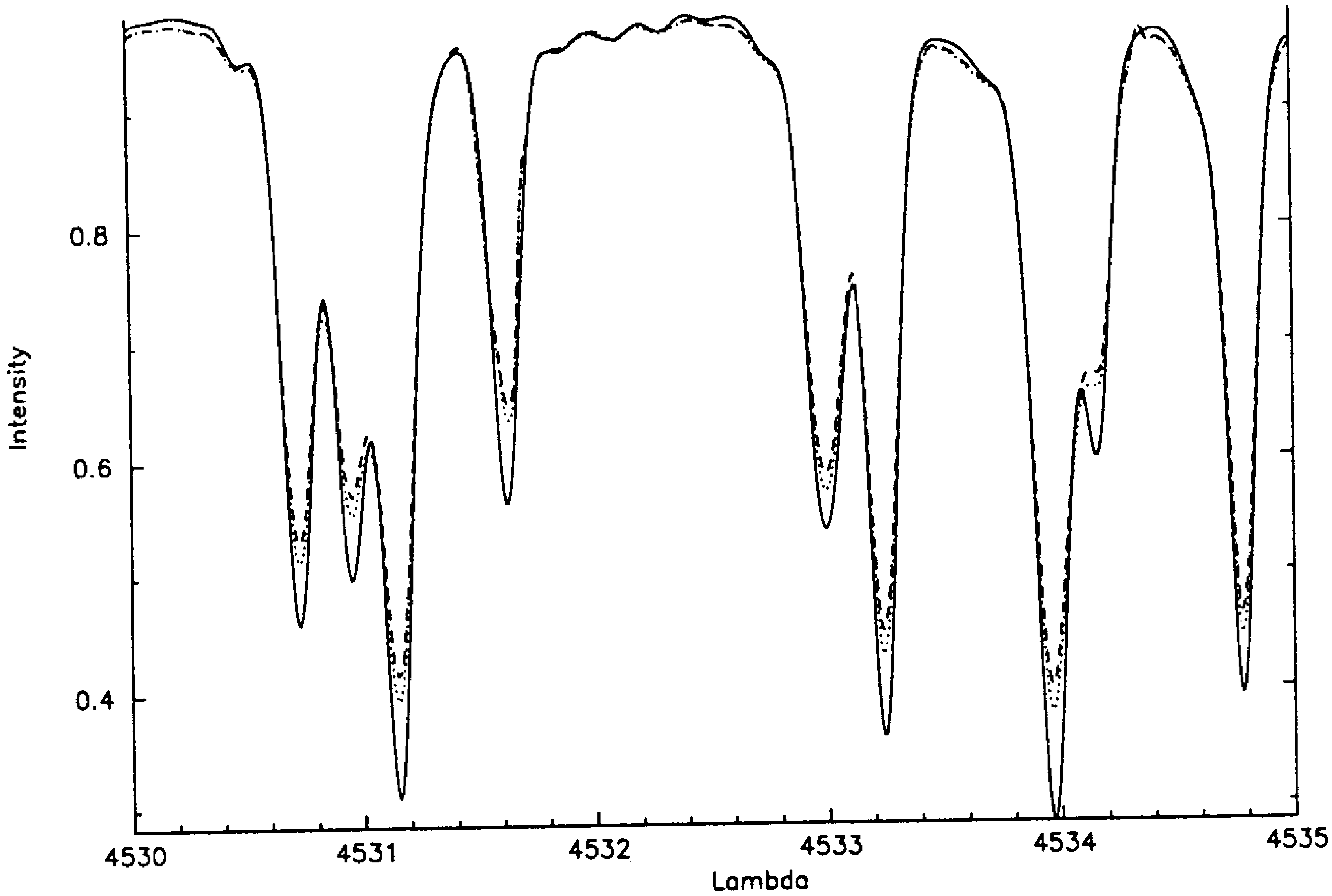

Figure 3. The FTS solar spectrum (solid line) convolved with the comparison instrumental profile, the sky spectrum without any scattered light correction (dashed line) and the sky spectrum with scattered light correction of 4% (dotted line).

go further from line center by moving the line off the end of the chip, but this eliminates halation effects.

By adding the profiles of many suitable lines in a not too wide spectrum region, one can also beat down the noise as well as effectively increasing the number of sample points contained within the core of the instrumental profile. Gulliver and Hill (1990) have taken this approach. In Figure 2, the central core determined by coadding 9 isolated, intensity weighted Fe and Ar hollow cathode comparison lines for a region centered on 4520 Å is shown with the laser central core included for comparison. There was no detectable difference in width of the instrumental profile for Fe versus Ar lines. There is, however, a clear difference in width between the laser and comparison profiles, the cause of which is not known. Experience with many such profiles has led to the conclusion that the instrumental profile width does vary by some 10% from one region, or observing epoch, to another. Thus for best results, the instrumental profile should be determined at each region during each observing run. Given the practical difficulties of using the laser and of matching wavelengths, this is more readily done by coadding comparison lines. For the convolution of the instrumental profile with another spectrum, it is the core which is most important and not the wings found in the laser instrumental profile. These wings may however contribute to the scattered light.

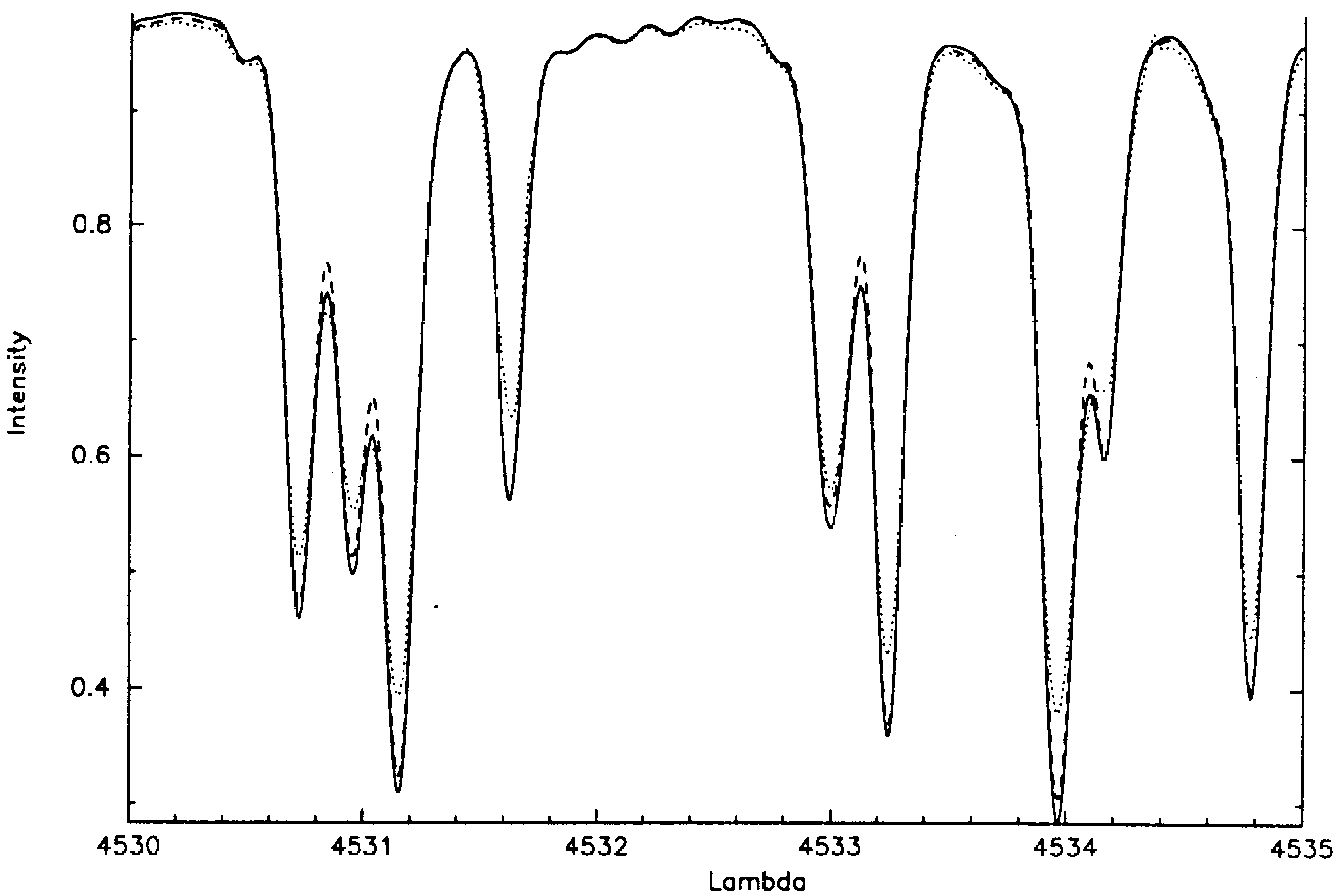

Figure 4. The FTS solar spectrum convolved with the comparison instrumental profile (solid line), the FTS solar spectrum convolved with the laser instrumental profile (dashed line) and the sky spectrum with scattered light correction of 4% (dotted line).

Many ingenious ways have been proposed to measure the scattered light. One can consider it to be composed of two components, one due to dust on mirrors and in the air, bubbles in lenses, and all other randomly oriented imperfections and a linearly scattered light that is directed along the dispersion direction and is produced by the slit and the grating. However, these approaches often are not transparent. It is clear that in the S/N > 100 era, we must correct our spectrograms for scattered light and have a straightforward procedure if possible to do so. With an array detector such as a CCD, a large percentage of any isotropic component will be removed as part of a background subtraction.

Fortunately Kurucz has provided the community with a tool that we can use, namely, a high dispersion solar spectrum taken with a Fourier Transform Spectrometer. Such a device has no scattered light. This means if we take a spectrum of the Sun with a particular spectrograph, we can compare it to Kurucz's FTS spectrum and derive the scattered light. Before doing so we must broaden the FTS spectrum so that both have the same resolution. The appropriate convolution is with the measured instrumental profile, which is the true profile less the far wings. Scattered light will reduce the line depths in the observed spectrum.

This technique has some practical problems. First, one needs to find a bright enough source to get a high S/N spectrum. The surface brightnesses of the Moon even at full, Venus, and the Galilean satellites of Jupiter are not that high. Certainly we do not want to observe the Sun with a large telescope. The only alternative is to observe the sky, usually during the day. Second, light from the sky is polarized and most coudé mirror trains can polarize unpolarized light. Some detectors have different responses to the different types of polarized light. Third, some of the lines in the Sun are affected by magnetic fields. But for at least modest spectral regions these effects are thought to be small. Fourth, there is a problem in normalization. The solar spectrum is spectral type G2 V and parts of it have very few continuum points. Extinction and scattering in the Earth's atmosphere as well as the spectral response of the telescope and instrument can affect the relative positions of the high points. An alternative is to use FTS spectra of several bright sharp-lined stars as the comparison sources instead of that of the Sun. Fifth, a laser is a coherent source. Some type of diffusers have to be used, but this is not a major problem. However, sixth, laser light, used to measure the instrumental profile, is polarized and there are generally small but measurable effects over which somehow one needs to average. Despite these problems, a method or methods must be found to accurately, and efficiently, determine the instrumental profile and scattered light of any spectrograph.

For additional information on these subjects, we refer the reader to Unsöld (1955) and Gray (1992).

2. Some Specific Observations

We now discuss some attempts to include the instrumental profile and scattered light in the anaylsis of high S/N spectra. The daytime sky was observed with the DAO 1.2-m telescope using the coudé spectrograph and a 1872 pixel bare Reticon with 15μ pixels. The spectrum section discussed extends from 4530 - 4535 Å in wavelength steps of 0.035 Å with S/N = 1400 for the continuum.

As part of the rectification procedure, a scattered light correction was applied via the relation:

$$y'_i = \frac{y_i - s * \overline{y}}{1.0 - s}$$

where y'_i is the corrected intensity, y_i is the original intensity, s is the scattered light fraction and $\overline{y}$ is the mean of the original intensity. The result of applying this transformation, with s = 0.04, to the observed spectrum is illustrated in Figure 3. The FTS solar spectrum convolved with the comparison instrumental profile of Figure 2 is also shown for comparison. For the comparison, all three spectra have been renormalized to correct for the change in the continuum produced by either the scattered light correction or the instrumental profile convolution and, both sky spectra have been interpolated at the sampling interval of 0.01 Å of the FTS spectrum. The effect of applying the scattered light correction is clearly to deepen the lines as expected but, the agreement between the solar and sky spectra is less than satisfactory. It is estimated that a scattered light fraction of 0.15 would be required to bring the two into reasonable agreement but such a value is considered to be unrealistic.

The extended wings of the laser illuminated instrumental profile in Figure 1 might be expected to contribute some of the scattered light. To gauge the

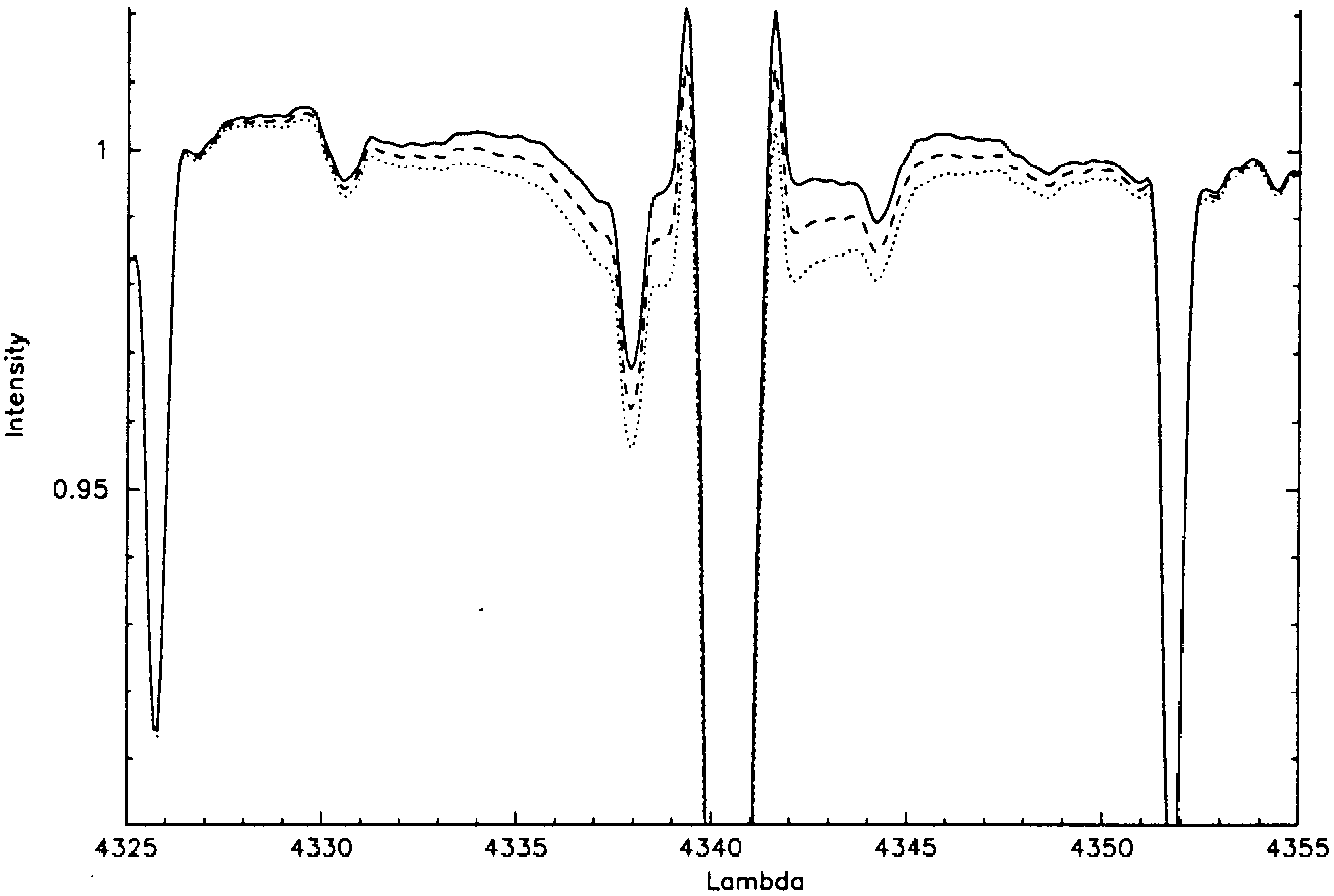

Figure 5. The ratio of the 9682 Hγ profiles of Vega corrected for 2.5% (solid line), 3.0% (dashed line) and 3.5% (dotted line) scattered light compared to Peterson's (1969) scanner profile.

importance of this, the FTS spectrum was convolved with the laser instrumental profile and the results are illustrated in Figure 4. Clearly, there is little difference between the two convolved FTS spectra and, just as clearly, neither show a satisfactory fit to the scattered light corrected sky spectrum. We are unable to isolate the source of this discrepancy except to state that it may result from one of the potential problems discussed above.

That the canonical value of 4% is reasonable can be confirmed using an alternative method. This involved the comparison of the observed Hγ profile with the Hγ photoelectric scanner profile of Vega (Peterson 1969). Vega was observed using the vacuum spectrograph of the McMath Solar Telescope in both single and double pass mode. The scattered light contribution was assessed at 0.2% ± 0.1% and was considered to be negligible. We have determined the scattered light fraction for two, entirely independent, DAO coudé spectrograph combinations: the 3261 (see Richardson 1968), and the 9682, which we have been discussing. The 3261 Reticon spectrum extends from 3950 - 4500 Å at a resolution of 0.6 Å and a mean S/N = 350 while the 9682 spectrum extends from 4321 - 4388 Å at a resolution of 0.08 Å and a mean S/N = 2900. In both cases the scattered light fraction was found to be 3.0% ± 0.5%. Although the 3261 results are more reliable because the wavelength coverage extends far beyond the wings of Hγ, the 9682 results are discussed for comparison with the results above.

Before comparing the 9682 profile with Peterson's profile considerable care had to be taken to ensure that both were rectified in a consistent manner. Peterson's profile, for example, had continuum points placed at ±70 Å of line center. However, an ATLAS9 / SYNTHE synthetic spectrum of Vega, using the model of Hill et al. (1996), indicates that the far wings of Hγ still reach an intensity of 0.993 at these points. Even more importantly, the 9682 spectrum extends to only -19 Å and +48 Å of line center. Both spectra were rectified by matching the intensity levels of the synthetic spectrum at designated points. Thus, for Peterson's profile, the intensity at ±70 Å was set at 0.993 while the 9682 levels at 4322.5, 4358.5 and 4378.5 Å were set at 0.843, 0.843 and 0.965, respectively.

Various scattered light corrections were then applied to the 9682 spectrum using the relation above. The result was also convolved with a Gaussian with FWHM of 0.3 Å to approximate the resolution of the scanner profile. The results for three values of the scattered light are shown in Figure 5. Since the scanner profile contains no lines and the core of Hγ is not sampled, any comparison among the ratio of the corrected 9682 to scanner profiles must be restricted to the line-free regions of the wings. The best choice is that for a scattered light contribution of 3% ± 0.5%.

The importance of accurate determinations of both the instrumental profile and the scattered light, especially at very high S/N, is obvious. We will continue to pursue both of these important side issues in the analysis of stellar spectra. Thus, we plan to determine the instrumental profile using a shorter wavelength laser and to determine the cross dispersion component of the scattered light using a CCD.

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