WAVELENGTH SHIFTS IN THE SOLAR PHOTOSPHERIC SPECTRUM

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Abstract. Wavelength shifts converted to velocities between solar lines observed at disc center and laboratory wavelengths of Fe I, Fe II, Ti I, Ni I, and Fe I lines in the near infrared are plotted as a function of the logarithm of their solar equivalent width in milliångstroms. The need for wavelengths based on the wavelength standards is stressed. A comparison of photographic Fe I solar wavelength is shown to agree, on the average, with Fourier Transform Spectrometer solar wavelengths within less than 0.5 milliångstroms. Using Balthasar's limb effect tables we convert the disc center velocities to limb velocities and find, though the scatter is large, that there is little evidence for a super-gravitational red shift.

1. Introduction: Wavelength Shifts in the Solar Spectrum

Wavelength shifts and line asymmetries of Fraunhofer lines have their origins in the various velocity fields of the Sun's atmosphere. The mid-1950s mark the division between theories that treated line formation in a static Sun, with a smooth layered surface that gives symmetrical line profiles, and theories based on a dynamic Sun with granulation that gives asymmetrical line profiles. Unsöld's (1955) book, *Physik der Sternatmosphären* covers the first period with over 2000 references to smooth atmospheres in stars and the Sun. Dravins' (1982) summary article covers the start of the second period with over 150 references to the dynamic Sun.

The advent of powerful computers made possible very realistic models of the Sun's atmosphere, which includes the gas-hydrodynamic nature of solar granulation together with the radiative transfer equations. Nordlund (1978, 1982) and Dravins, Lindegren and Nordlund (1981) were among those who pioneered this approach. Bruls' (1992) thesis with many references brings this up to date. Also see Bruls and Rutten (1992).

Richardson and Schwarzschild (1950) first published from their observations the spectra of solar granulation, along with a microphotometer trace, showing velocities of individual granules. A clear picture of supergranulation was obtained by Leighton using his technique of superimposing two sequential spectroheliograms taken at half of the five-minute oscillation period. This work was extended by Leighton, Noyes, and Simon (1962).

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After correction for the observer's motion, all Fraunhofer lines in the solar spectrum are red-shifted with respect to their laboratory wavelengths by the gravitational red shift. In addition, most weak to moderate strength lines show a red shift at the Sun's limb with respect to the Sun's center, while the very strong lines and, in particular, the resonance lines do not. This wavelength displacement is called the limb-effect. The term, super-gravity shift, was coined by Adam, Ibbetson, and Petford (1976) to represent the excess red shift of Fraunhofer lines at the extreme limb of the Sun, exceeding the Einstein gravitational red shift. Forbes' (1961) paper contains a history of the solar red shift.

2. Nadeau's Equation for Velocities at the Center of the Sun's Disk

Nadeau (1988) derived a simple equation for the solar radial velocities of iron lines observed at the disc center, in the ultraviolet and visible parts of the spectrum, by Pierce and Breckinridge (1973, 1974) and by Biémont *et al.* (1985) in the infrared,

$$V(\mathrm{m\ s^{-1}}) = -310 + 1.34(D - 37)e^{E/2.59}\,, \tag{1}$$

in which D is the percentage depth of the line from the local continuum and E, the excitation energy in electron volts. On examining this equation we see that the great majority of solar lines indicate motions outward in the solar atmosphere and only when D and E are large does it predict descent. Our observations of the vertical velocity of a few iron lines are not well represented by Nadeau's equation and prompted a re-examination with newer data. Equation (1) uses the line depth, D, as a measure of line strength, but when D is large there is little change in line strength as the line saturates and grows wings. This effect is shown in Figure 1, which plots depth, D, versus the logarithm of the equivalent width, W, in milliångstroms. It clearly shows the good correlation between the two and the effect of saturation as the line grows wings. It is because of this saturation that we choose to use log W rather than line depth D for several of our graphs.

3. Solar Wavelengths and Solar Photospheric Velocities

In order to make a valid comparison between solar and laboratory wavelengths, it is necessary that they be based on the same wavelength standards or that they be measured differentially at the same time with the same spectrograph equipment. As stated by Pierce and Breckinridge (1973, 1974) in their table of photographic-grating wavelengths 2919–9000 Å, the solar wavelengths are based on a list of thorium lines initially supplied by Zalubas and later published by Giacchetti, Stanley, and Zalubas (1970). Their paper and also a paper by Sansonetti and Weber (1984) give the accuracy of the thorium wavelengths.

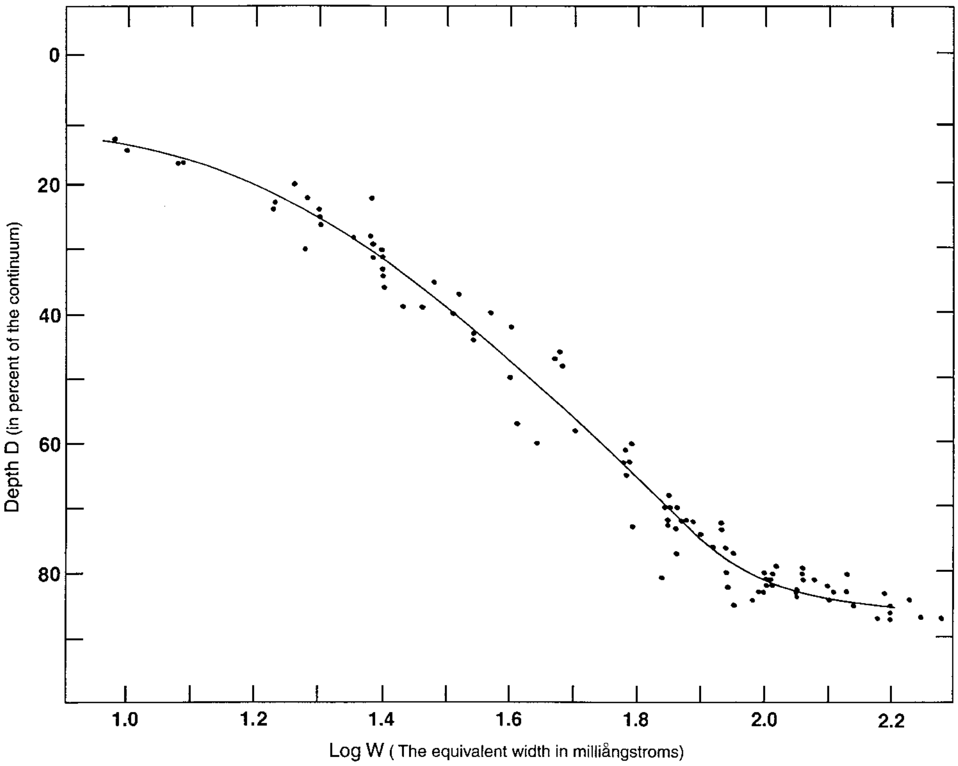

Figure 1. Solar line depths in percentage of the local continuum versus logarithm of the equivalent width at cos $\theta = 1.0$.

Today, nearly all the work in laboratory spectroscopy is based on Norlén's (1973) wavelengths of Ar I and Ar II, that where observed in low-pressure hollow cathodes with a Fabry–Pérot interferometer in a vacuum. This is the basis for the wavelengths of 9501 lines of Fe I obtained with a Fourier Transform Spectrometer and high-resolution grating spectroscopes published by Nave *et al.* (1994). Both the observed wavelength and the Ritz wavelength (wavelengths determined from energy levels) are given in their publication along with a table giving estimates of the wavelength uncertainties for different wavelengths. For a full discussion of the problem of wavelength calibration of Fourier Transform spectra, the reader is referred to the work of Learner and Thorne (1988).

The photographic wavelengths used in Figure 2 were measured with a Grant comparator, which displays on a cathode ray screen a photometric trace of a short region of the spectrum and its electronically reversed image. The forward and reverse traces are brought into coincidence for the bottom 5–10% of the line by movement of the carriage. This, however, conceals any remaining asymmetry in the bottom of the line. In photoelectric measures the wavelength is determined from line fitting and locating the position of the minimum. Neckel and Labs (1990) show

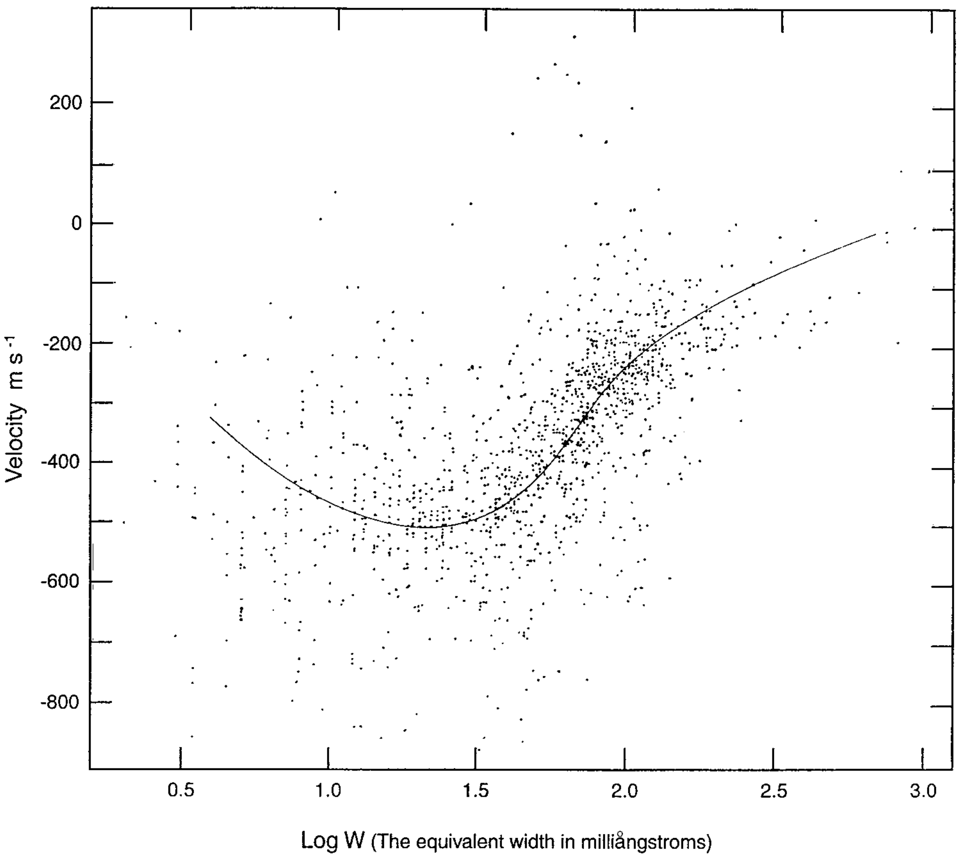

Figure 2. Line shifts in milliångstroms converted to velocities at disc center for 1295 Fe I lines, in meters per second plotted as a function of logarithm of the equivalent width in milliångstroms.

TABLE I

Statistics of the solar disc-center wavelengths of Fe I lines: λ (Allende Prieto – García López) – λ (Pierce – Breckenridge) in milliångstroms

λ	No. of lines	Δλ	σ (standard deviation)
4000–4500	480	−0.07	1.35
4500–5000	325	−0.09	1.34
5000–5500	290	+0.46	1.47
5500–6000	195	+0.14	1.30
6000–7960	183	+0.36	1.55

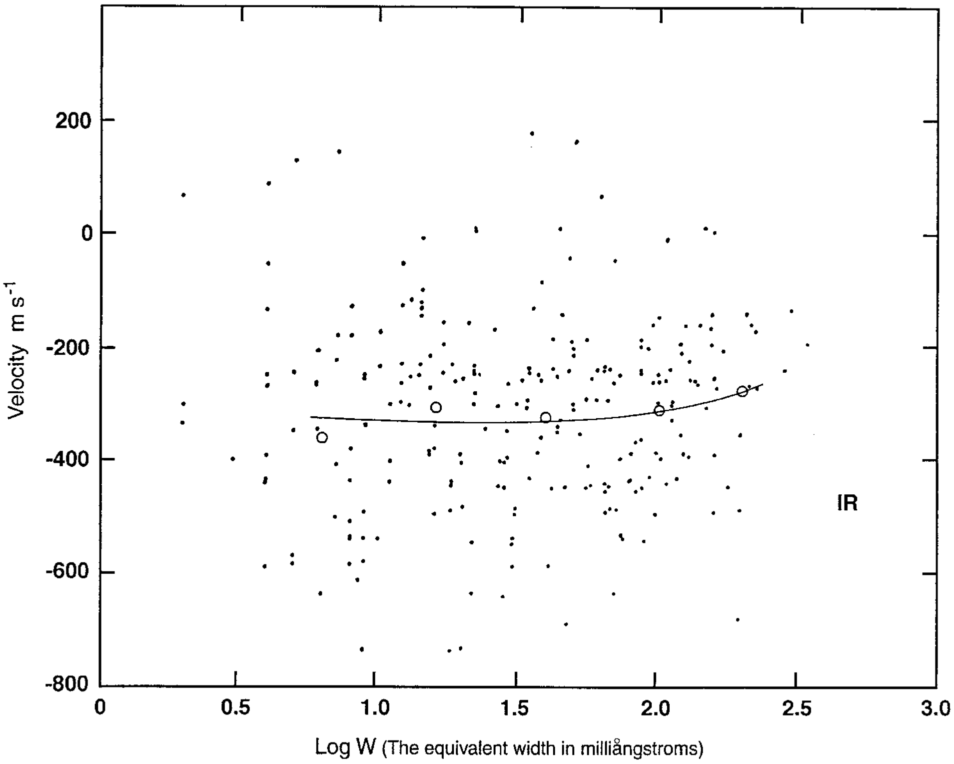

Figure 3. Velocities at the Sun's disc-center (cos $\theta = 1.0$) versus the logarithm of the equivalent width in milliångstroms for Fe I lines in the wavelength interval, 1.1 μ to 2.5 μ.

that the position of the minimum can be determined to about 4 m s^{-1}. However, differences in wavelengths between lines of different strengths can be momentarily be as large as 500 m s^{-1}.

Recently, Allende Prieto and García López (1998a, b) published a catalogue of wavelengths of 4947 lines from FTS solar atlases for both flux and disc-center observations. Line positions were determined by fitting a fourth order polynomial to about 25 points in a 50 milliångstroms interval around the line minimum. They find from 42 lines that the FTS wavelengths and the Pierce-Breckinridge photographic wavelengths agree on the average within 0.72 milliångstroms. A more extensive comparison is given in Table I.

The agreement between the two sets of wavelengths is excellent. The one from the FTS spectra is based on Norlen's (1973) interferometrically determined Ar II wavelengths; the other which is photographic is based on the weighted values of interferometrically determined thorium wavelengths.

Solar wavelengths are greatly influenced by solar oscillations. The long averaging time (about 30 min) used in creating a Fourier Transform spectrum greatly reduces the problem; it was minimized by Pierce and Breckinridge (1973, 1974) by

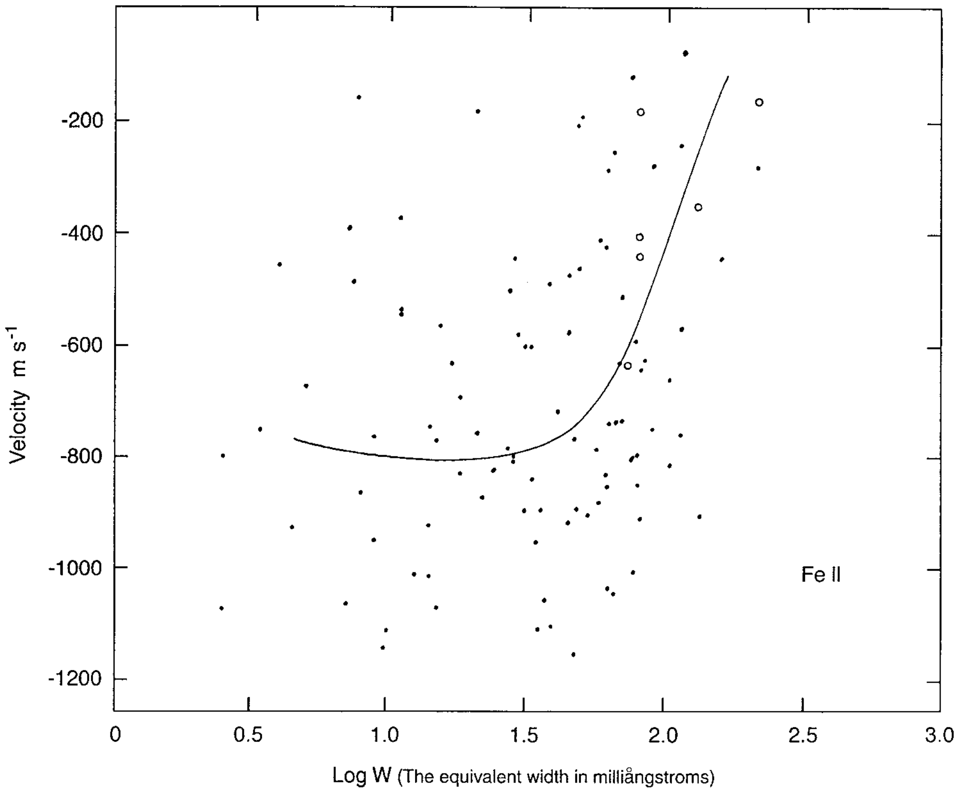

Figure 4. Velocities at cos $\theta = 1.0$ versus the logarithm of the equivalent width, W, in milliångstroms for Fe II lines. The small circles are from our observations.

averaging many separate spectra and by integrating over a small area at the center of the disc.

Allende Prieto and García López (1998) were the first to publish a graph showing the close relationship between line shifts (velocities) and the logarithm of the equivalent width of Fraunhofer lines at solar disc center. Their graph (Figure 2(a) in their paper) was based on 1446 wavelengths determine from FTS spectra. At the same time we had prepared a similar graph (Figure 2), extending to weaker lines, from the solar wavelengths of Pierce and Breckinridge (1973, 1974) for Fe I lines in the wavelength interval $\lambda\lambda$ (4000–8700) and the Ritz wavelengths of Fe I published by Nave *et al.* (1994) The logarithm of equivalent width W in milliångstroms, is from Moore, Minnaert, and Houtgast (1966). The lines were divided according to excitation potential into four groups. The first group included lines from 0.0 to 1.49 V, the second 1.5 to 2.99 V, the third 3.0 to 4.49 V, the fourth 4.5 V and upward. This gave 84 lines in the first group, 264 lines in the second group, 810 lines in the third group and 137 lines in the fourth group. Each group was plotted separately. Since there was no discernible difference between each

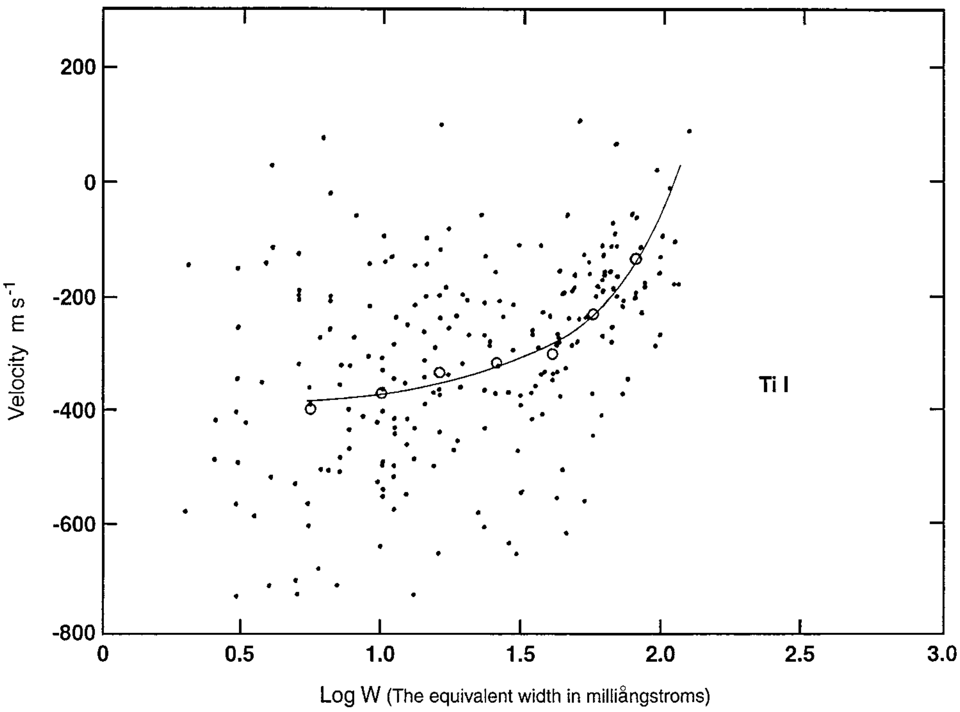

Figure 5. Velocities at cos $\theta = 1.0$ for Ti I. W is the equivalent width in milliångstroms.

group, they were combined into one plot of 1295 lines which is Figure 2. The solid line is a free hand fit through the points.

4. Solar Velocities for Fe I in the Infrared, Fe II, Ti I, and Ni I

Biémont *et al.* (1985) observed, by Fourier transform spectroscopy, the near infrared spectrum of Fe I in the laboratory and in the Sun. Their tables, covering the region 1.1 μ to 4.16 μ, give wave numbers for the lines to two decimal places for both spectra. The solar velocities computed from these wave numbers when combined with the equivalent widths from Mohler (1955) are illustrated in Figure 3. At these wavelengths we are at the minimum of the H^- absorption and might expect to see deep into the solar atmosphere. As the figure illustrates, we do not find the change in velocity versus line intensity that we found for the visible part of the spectrum. There are no strong infrared Fe lines. Using bisectors to determine infrared solar wavelengths, Hamilton and Lester (1998) plotted the velocities versus wavelength for four different line depths. The groups of lines located at 0.8 μ, 1.6 μ and the infrared interval (2.1 μ to 4.1 μ) show a decrease in velocity from about -500 m s^{-1} to -100 m s^{-1} at the longest wavelengths.

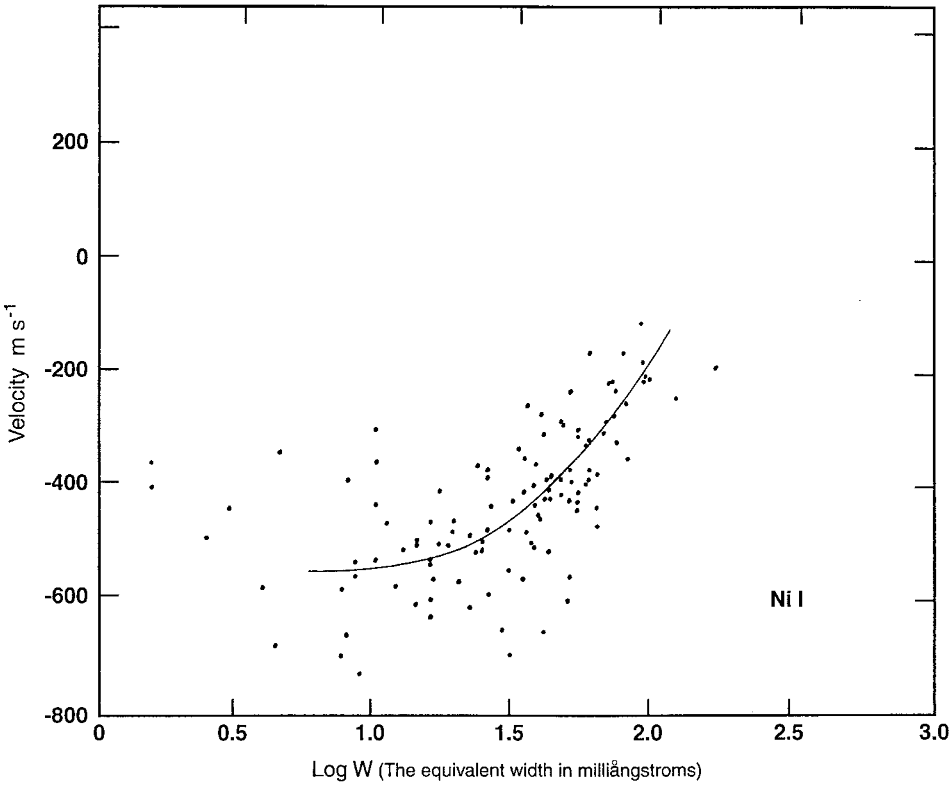

Figure 6. Velocities at disc-center ($\cos\theta = 1.0$) for Ni I lines. W is the equivalent width in milliångstroms.

We are not limited to the Fe I spectrum. A list of laboratory wavelengths and terms for Fe II is found in the paper by Johansson (1978). The solar spectrum of Fe II is treated in great detail by Dravins, Larsson, and Nordlund (1986). In Figure 4 we plot the wavelength shifts, in terms of velocity, as a function of the logarithm of the equivalent width W of each line. The very large negative velocities coming from the hottest cells of the granulation field are reproduced.

The spectrum and term system of neutral titanium, Ti I, given by Forsberg (1991), when combined with the photographic solar spectrum in a velocity versus log W plot is shown in Figure 5. The mean titanium curve falls considerably above the same curve for Fe I. In addition, the points are widely scattered. Forsberg gives wavelengths to three decimal places. This, plus the hyperfine structure of Ti I may contribute to the discrepancy.

The mean curve for Ni I, Figure 6, obtained from the accurate wavelengths of Ni I by Litzen, Brault and Thorne (1993), falls almost exactly on that of Fe I. An isotope shift, ^{58}Ni–^{60}Ni, of 10 mÅ to the violet for the visible spectrum has been suggested by Brault and Holweger (1981). However, this would displace the curves by 545 m s^{-1} at λ5600 and we do not find this to be the case.

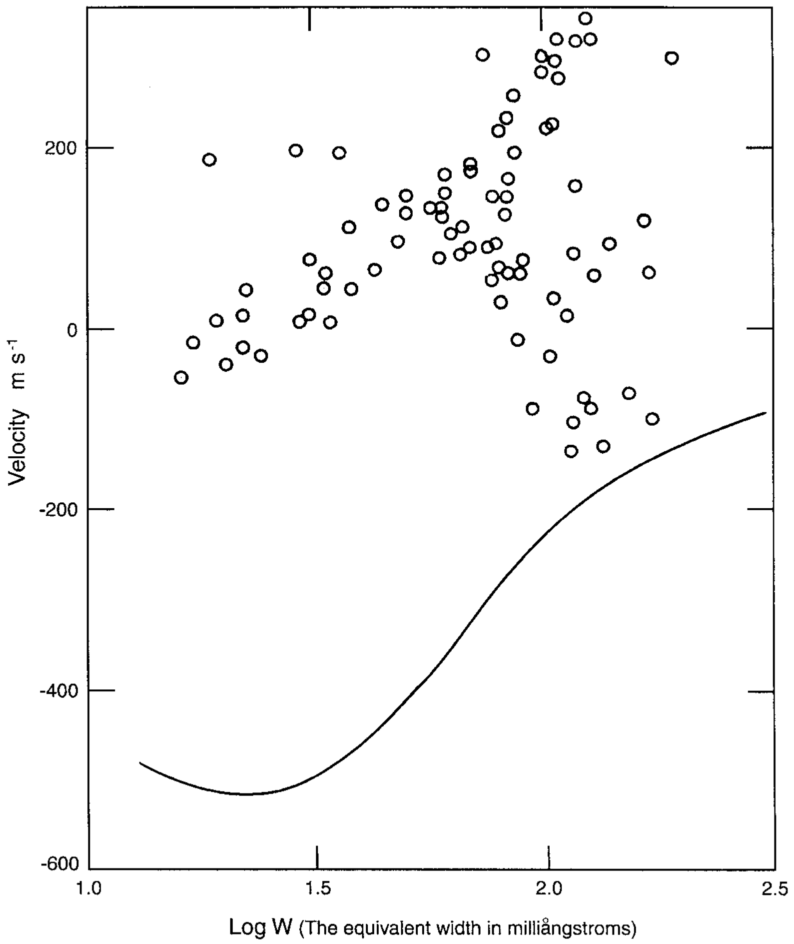

Figure 7. The solid line is the average wavelength displacement converted to velocities in meters per second of Fe I lines at the disc center, cos $\theta = 1.00$, from Figure 2. The circles are limb velocities, cos $\theta = 0.00$, obtained by adding the *limb effect* to the mean curve for disc center.

5. Limb Wavelengths, Converted to Velocities and the Super-Gravity Shift

Balthasar (1988) has published the limb effect for 193 solar lines, primarily from iron, but also from a few other elements in the range $\lambda\lambda$ 4800–6302. His tables give differential measures of wavelength between disc center, cos $\theta = 1.00$, and the limb point, cos $\theta = 0.112$, together with 11 points in between. For most of the lines a least-square parabola makes a good fit to the observations. Extrapolating to the limb, cos $\theta = 0.00$, and converting the center to limb change from wavelengths to velocities, then adding them to the *mean* velocity curve for disc center (Figure 2), we obtain the limb velocities which are plotted as small circles in Figure 7. The scatter is large. There is, on average, a residual red shift of about 100 m s^{-1} at the limb. We conclude that there is probably no supergravitational red shift. Better observations may serve to refine this statement.

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