THE CENTER-TO-LIMB WAVELENGTH SHIFT OF A NUMBER OF FRAUNHOFER LINES

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Abstract. The center-to-limb wavelength shifts of the cores of faint, medium and strong Fraunhofer lines are presented: Fe I 3767, Ca II 3968, Ce II 4222, Ca I 4227, Na I 5896, Ba II 6497, and K I 7699.

1. Introduction

The wavelength displacement of weak Fraunhofer lines, between the center and limb of the Sun's disc, is considered to be due to the correlation between the brightness field and the velocity field of solar granulation. Also, since these two fields vary with height in the Sun's atmosphere, the contribution function to the line profile is affected, resulting in varying displacements between core and wing, i.e., an asymmetrical profile. Additionally, in order to explain the complex behaviour of the shifts, Beckers and Nelson (1978) found it necessary to include horizontal small-scale granular velocities in addition to the vertical. When one considers very strong lnes, whose cores presumably form above the convection zone of the granulation field, one must consider large-scale horizontal and vertical flows as contributors to the wavelength displacements in the line core. Furthermore, if solar wavelengths are compared to terrestrial wavelengths, an additional shift is observed – the Einstein gravitational redshift. It is apparent, that our only hope of resolving these various components is through studies of the asymmetries and wavelength shifts of a number of lines formed at different effective depths using laboratory wavelengths as standards. In this paper, we consider only the observational side of the problem and only the center to limb shift of the very center (core) of several lines. Though we have measured wavelengths on an absolute scale, and we will so present them, the problem of systematic errors in the absolute wavelength and the discussion of laboratory standards requires a separate discussion which will be the subject of another paper.

Forbes (1961) published a history of the solar redshift problem up to 1962. The more

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recent work on line asymmetries and wavelength shifts has been critically reviewed by Dravins (1982) and again by Dravins *et al.* (1981). Andersen (1984) selected Fe I 5576, a $g = 0$ line for study. Bathasar (1984), using Fourier transform spectra found asymmetries and wavelengths for 143 lines. Cavallini *et al.* (1985) have used a Fabry–Pérot spectro-interferometer to observe three weak Fe I lines around 6300 Å in quiet and active regions. From these and other papers the reader can easily trace the work in the field.

For our purposes, we wish to draw attention to a few older results which relate to the present work. Adams (1910) in a long and detailed investigation of the center to limb displacement (disc center and one point near the limb) covering the wavelength region from 3740–6573 Å came to several conclusions – since, largely ignored:

His conclusion in part were:

(1) The lines of hydrogen, H and K of Ca II and other strong Fraunhofer lines show no appreciable displacement.

(2) The lines of elements of high atomic weight, such as lanthium and cerium, show very small displacements.

(3) The displacements for Ti, V, and Sc are considerably smaller than those for Fe and Ni.

(4) A few lines are shifted to the violet.

2. The Observational Procedure

All observations were obtained in double pass through the 13.5 m spectrometer (Pierce, 1964), by alternately scanning a Fraunhofer line and then the corresponding laboratory line. An interferometer system controlled the grating rotation. The output of each scan, taking 2–4 s, was accumulated in the computer until a low noise profile resulted. A magnetic tape record was then available for further processing.

The slit, width 0.2 mm, length 10 mm, oriented tangentially to the limb, was sequentially placed at 0.5, 2.25, 10 mm, etc., from the limb across the diameter of the disc. A total of 25 traverses of the Sun's image makes up one observation of one Fraunhofer line.

3. Data Analysis and Results

The complete correction for the observer's motion relative to the point of observation on the Sun was obtained via techniques outlines by Howard and Harvey (1970) and by numerically differentiating the quantities tabulated in the *Astronomical Almanac*.

Most observers of the redshift have made their comparison with weak solar lines or with lines of moderate intensity as exemplified by the work of Adams (1959), Higgs (1960), Forbes (1962), and Salman-Zade (1969). The result is a monotonic increase in the observed wavelength as the limb is approached. The work of Balthasar (1984) and

Cavellini *et al.* (1984) are recent examples of these observations. We find agreement with this trend in the weak line Ce II 4222, see Figure 1, a line of 22 milli-ångström equivalent width, which incidently contradicts the second statement of the work of Adams cited above, that rare-earth lines show small displacements. The medium strength Ba II 6497 line, equivalent width 98 milli-ångström, also illustrated in Figure 1, shows a much reduced variation between center and limb.

Before proceeding we should comment on wavelengths and line asymmetries. The bisector of most Fraunhofer lines exhibit the well-known 'C' characteristic at disc center. This behaviour changes character as one approaches the limb; generally, the asymmetry is much reduced, it may even disappear or change sign. For an asymmetric line, a

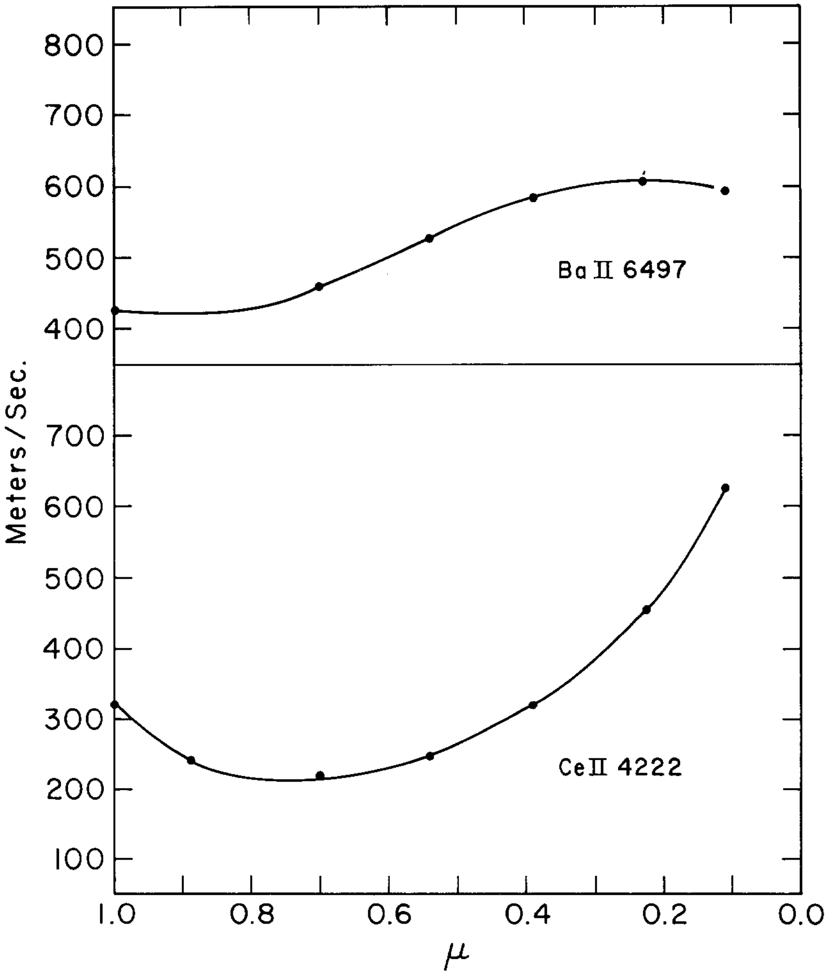

Fig. 1. The center-to-limb variation in wavelength (expresed in meters per second) for two Fraunhofer lines compared to their laboratory wavelengths from a hollow cathode. The displacements of the solar lines are to the red at the limb ($\mu = 0$).

'wavelength' is indefinite and we must define precisely what is meant by a number representing 'wavelength'. Fitting the bisector with a polynomial and extrapolating its intersection with the line minimum would give a meaningful value of the wavelength of the core of the line. However, we have often observed large distortions in the line profile caused by local velocity fields. This is well illustrated in Snider's (1970) paper of the solar potassium line at 7699 Å. Hence, as a matter of expediency, but principally because there is some averaging of the asymmetrics in the core, we have chosen to fit by least squares a parabola to the core of the line (the bottom 10%). Note, since the lines become more symmetrical at the limb (and unfortunately wider) the true wavelength becomes better defined.

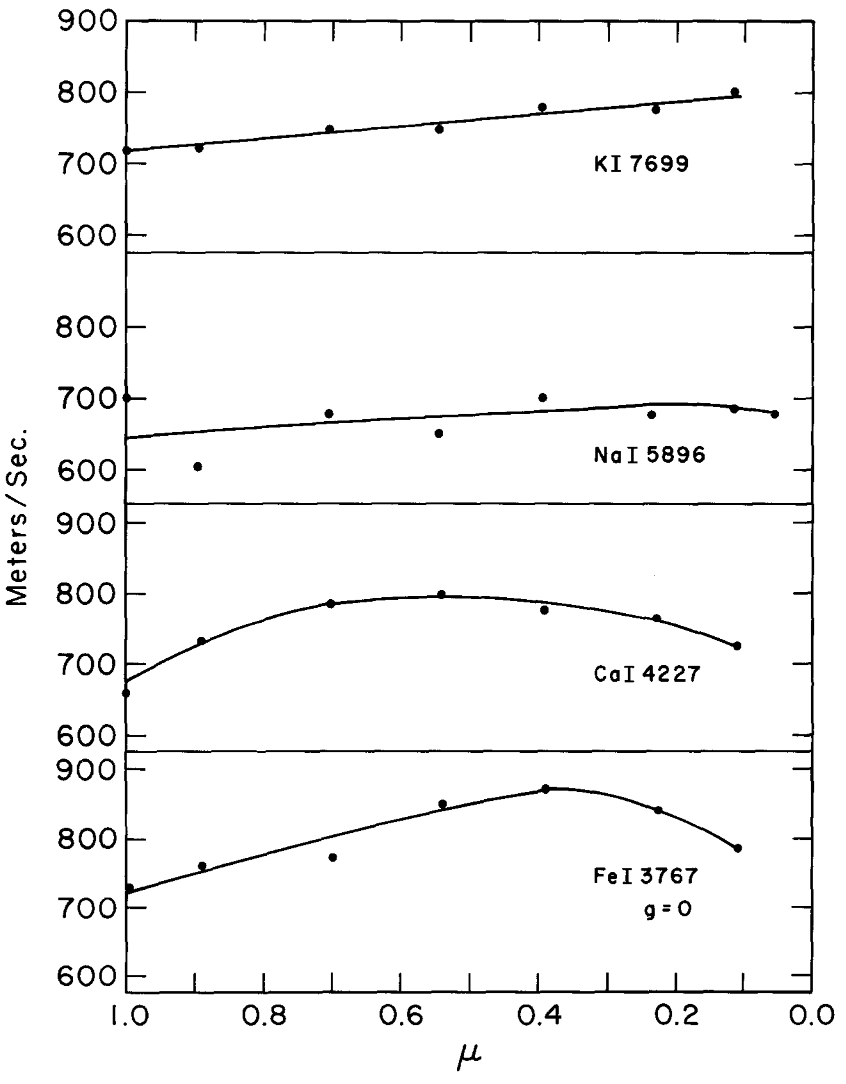

Fig. 2. Center-to-limb shift in wavelength of strong Fraunhofer lines.

We agree with Adams's (1910) statement that strong Fraunhofer lines show no appreciable displacement between center and limb. Figure 2 shows our measures for the core of a magnetically insensitive line Fe I λ3767, and for Ca I λ4227, Na I λ5896, and K I λ7699. The observed standard deviation of a single observation is about 150 m s^{-1}. When observations from 3–4 days are combined – 25 traverses of the Sun's diameter – as represented by the points in Figure 2, the scatter is reduced to less than 50 m s^{-1}. Although a formal error can be computed for each point, we feel that the scatter of points around the free hand curves best illustrates the precision of the measures. Listed in the body of Table I are the observed redshifts in meters per second. The first column gives the element, the second the wavelength, and the third the equivalent width in milli-ångströms. The fact that there is but little variation in wavelength center-to-limb implies a decoupling between the granular velocity field and the brightness field for these strong lines.

Measures of Ca II (Fraunhofer H_3) shows a completely different behaviour as illustrated in Figure 3. The wavelength was obtained from the axis of a parabola fitted

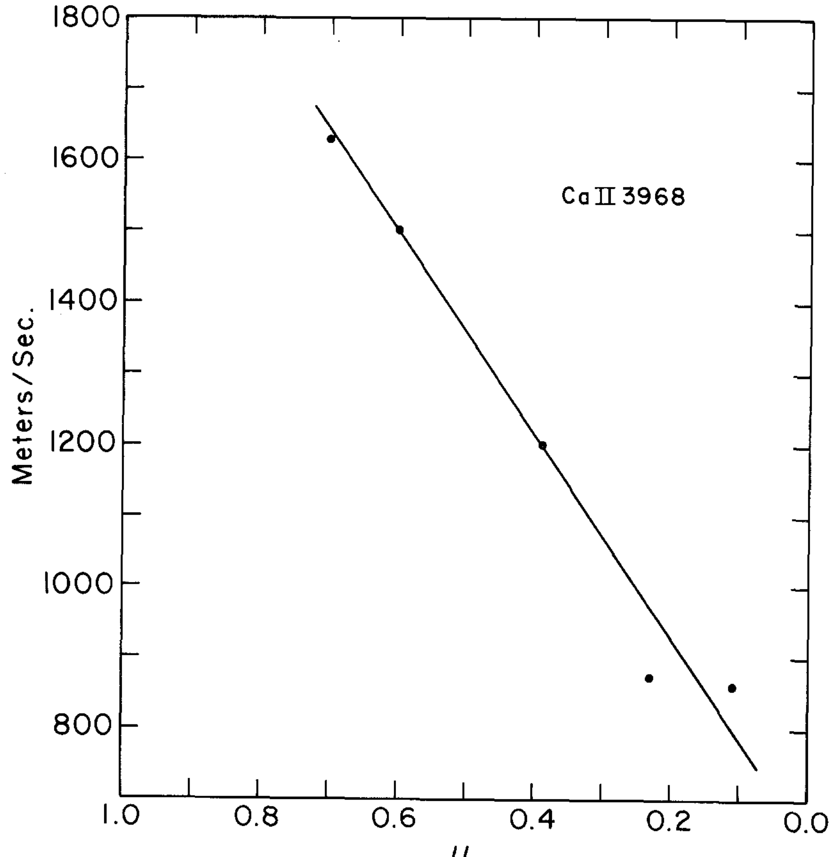

Fig. 3. The center-to-limb shift in the wavelength of the core H_3 of the strong Ca II line. The points exhibit a strong downflow at disc center (redshift) decreasing to the Einstein redshift of 636 meters per second at the limb.

TABLE I

Observed redshift in meters per second

Element	Wavelength	Eq. width	μ						
			1.00	0.89	0.70	0.54	0.39	0.23	0.11
Fe I	3767	820	726	760	772	849	871	840	783
Ca II	3968	15467			1631	1498	1198	873	860
Ce II	4222	22	320	240	218	248	319	453	624
Ca I	4227	1476	659	731	774	794	773	759	719
Na I	5896	564	649	605	673	644	696	672	677
Ba II	6497	98	425		461	526	582	604	591
K I	7699	154	720	721	745	748	774	768	796

Note: For Ca II the μ value of 0.54 should read 0.60. The Na I line has a redshift at $\mu = 0.05$ equal to 620 meters per second.

to the bottom 50% of H_3. The scatter of observation was very large, approximately 500 m s^{-1}, hence, a large number of observation made on several days were required to obtain the low scatter shown in Figure 3. A least square fit and extrapolation of a straight line to disc center gives 2070 m s^{-1}; subtracting the gravitational redshift gives a descent velocity of 1440 m s^{-1}. The behaviour is not a new result for already St. John (1910) concluded from a detailed study of the wavelengths of K_3 of Ca II at various positions on the solar disc that the calcium vapor has a descending motion over the surface of the Sun of 1.14 km s^{-1}. These measurements, like ours, were made outside the brilliant flocular regions away from spots. St. John and Babcock (1924) in summarizing a wide range of observations suggested a scheme of circulation in the Sun's atmosphere that included a downward motion, as observed in Ca II H and K of 0.5 km s^{-1}. Using a line-center-magnetogram technique Giovanelli and Slaughter (1978) measured – in magnetic elements or near them – a zero downflow in the highest levels of the atmosphere (however, much lower than H_3). Thus the picture remains confused.

Finally, returning to Adams's fourth conclusion that a few lines are shifted to the violet it can be shown that this effect is due to blends.

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