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# THE ABUNDANCES OF THE ELEMENTS IN THE SOLAR PHOTOSPHERE—VI

## Rubidium

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*Summary*

Low noise photoelectric scans of the Rb I resonance lines ($\lambda\lambda$ 7800 and 7947) have been obtained with the Oxford spectrometer. An analysis results in an improved abundance determination.

$$\log N(\text{Rb}) = 2{\cdot}63$$

on the standard scale where $\log N(\text{H}) = 12{\cdot}00$.

1. *Introduction.* Rubidium is represented in the photospheric spectrum by the $5s\ {}^2S$–$5p^2P^\circ$ resonance lines of the neutral spectrum (Rb I), which appear as weak lines at 7800 and 7947 Å. Goldberg, Müller & Aller (1960, hereafter referred to as GMA) have given the rubidium abundance as

$$\log N(\text{Rb}) = 2{\cdot}48$$

on the standard scale where $\log N(\text{H}) = 12{\cdot}00$.

This paper reports on a new investigation of the Rb I resonance lines and presents a discussion of the abundance of rubidium in the Sun. The principal novel feature is the use of improved observations of the Rb I lines in the photospheric spectrum. The reasons for the emphasis on improved observations are twofold. Firstly, accurate oscillator strengths for the resonance lines were available to GMA (see Section 3). Secondly, the predicted equivalent width of a resonance line of an element such as rubidium, which is predominantly ionized throughout the photosphere, is insensitive to the assumed model atmosphere. Therefore, a revision of the rubidium abundance can be significant only if it is derived from observations superior to those available to GMA.

2. *Observations.* The spectral regions of the Rb I resonance lines were scanned with the Oxford photo-electric spectrometer (Blackwell, Petford & Mallia 1967). At a dispersion of 3·6 mm/Å the exit slit width was given by $\lambda/\Delta\lambda = 3{\cdot}6\ .\ 10^5$. Scans of the region around $\lambda$ 7800 were taken at the centre of the disk (6 scans) and near the limb at $\cos\theta = 0{\cdot}3$ (6 scans). The longer wavelength line was observed only at the approaching (east) limb (8 scans) in order to separate it from a nearby water vapour line. An integration time of 1 s per data-point per scan was used.

Rubidium exists as the two isotopes, $\text{Rb}^{87}$ and $\text{Rb}^{85}$. Each isotope contributes two hyperfine components. Accurate wavelengths in standard air for the components of the resonance doublet were calculated from the term analysis of Johansson (1961). The relative intensities of the four components in each line were calculated from the assumption that the solar isotopic ratio is equal to the terrestrial value

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($Rb^{87}$ : $Rb^{85}$ = 3 : 1) and the standard formulae for the relative intensities in hyper-multiplets were used (Condon & Shortley 1951). Details of the wavelengths and relative intensities are given in Table I.

TABLE I

*The Rb I resonance lines: 5s $^2S$–5p $^2P^\circ$*

| Wavelength $\lambda_{air}$ (Å) | Isotope | Transition | Relative intensity of the hyperfine components |
|---|---|---|---|
| 7800·321 | $Rb^{87}$ | $^2S_{1/2}[F = 2]$–$^2P^\circ_{3/2}$ | 0·170 |
| 0·293 | $Rb^{85}$ | $^2S_{1/2}[F = 3]$– | 0·425 |
| 0·232 | $Rb^{85}$ | $^2S_{1/2}[F = 2]$– | 0·303 |
| 0·176 | $Rb^{87}$ | $^2S_{1/2}[F = 1]$– | 0·102 |
| 7947·657 | $Rb^{87}$ | $^2S_{1/2}[F = 2]$–$^2P^\circ_{1/2}$ | 0·170 |
| 7·629 | $Rb^{85}$ | $^2S_{1/2}[F = 3]$– | 0·425 |
| 7·565 | $Rb^{85}$ | $^2S_{1/2}[F = 2]$– | 0·303 |
| 7·513 | $Rb^{87}$ | $^2S_{1/2}[F = 1]$– | 0·102 |

2.1 5s $^2S_{1/2}$–5p $^2P^\circ_{3/2}$. The stronger line of the doublet falls on the red wing of the Si I line 3d $^3F^\circ_2$–6f $^3G_3$ with $\lambda_\odot$ = 7800·000 Å. The Si–Rb blend was observed both at the centre of the solar disk (Fig. 1) and at the limb position $\cos\theta = 0{\cdot}3$ (Fig. 2). The Rb I line is clearly visible in both tracings. The peak wavelength for the feature identified as Rb I is estimated to be 7800·285 ± 0·010 and 7800·290 ± 0·010 Å on the centre and limb spectra respectively. In the latter determination the Doppler shift from solar rotation was eliminated through an interpolation from neighbouring solar lines. The predicted wavelength for the centre of gravity of the line is $\lambda_{air}$ = 7800·268 Å. The observed wavelength (mean of centre and limb spectra) is 20 mÅ to the red of the predicted wavelength. This red-shift is in good agreement with the predicted gravitational redshift of 17 mÅ.

The profile of the Rb I line was obtained on the assumption that the Si I line has no intrinsic asymmetry. This assumption is discussed below. On reflection about the Si I line centre, subtraction of the undisturbed blue wing provides the profile for the Rb I line. A straightforward subtraction of profiles is considered justifiable except close to the peak of the Si I line (see Figs 1 and 2). Fig. 3 shows a comparison of the observed and theoretical profiles for the Rb I line. The latter profiles are derived by using the model solar atmosphere, which was given in earlier papers of the present series (Lambert 1967; Lambert & Warner 1967) with the simple model for the microturbulent velocity field proposed by Waddell (1958). The microturbulence is anisotropic with constant vertical and tangential components of 1·8 and 3·0 km $s^{-1}$ respectively. The equivalent widths obtained from the best fitting theoretical profiles are:

$$\text{at the centre of disk, } W_\lambda = 5{\cdot}3 \pm 0{\cdot}5 \text{ mÅ};$$
$$\text{at } \cos\theta = 0{\cdot}3, \quad W_\lambda = 8{\cdot}9 \pm 1{\cdot}0 \text{ mÅ}.$$

The observed profile at the centre of the disk is considerably broader than the theoretical profile; in particular, it should be noted that the extensive blue asymmetry cannot be attributed to Rb I. This asymmetry is effectively absent from the limb spectra. The presence of this feature necessitated the determination of the equivalent width of the Rb I line from a fitted profile.

2.2 $5s\,^2S_{1/2}$–$5p\,^2P^\circ_{1/2}$. The weaker Rb I line is blended with a weak water vapour line (see Fig. 4). The blend was observed at the approaching (east) limb in order to increase the line separation. The separation is incomplete and the Rb I line is discernible as a break in the blue wing of the $H_2O$ line. The Rb I equivalent width could not be obtained by reflection of the observed red wing of

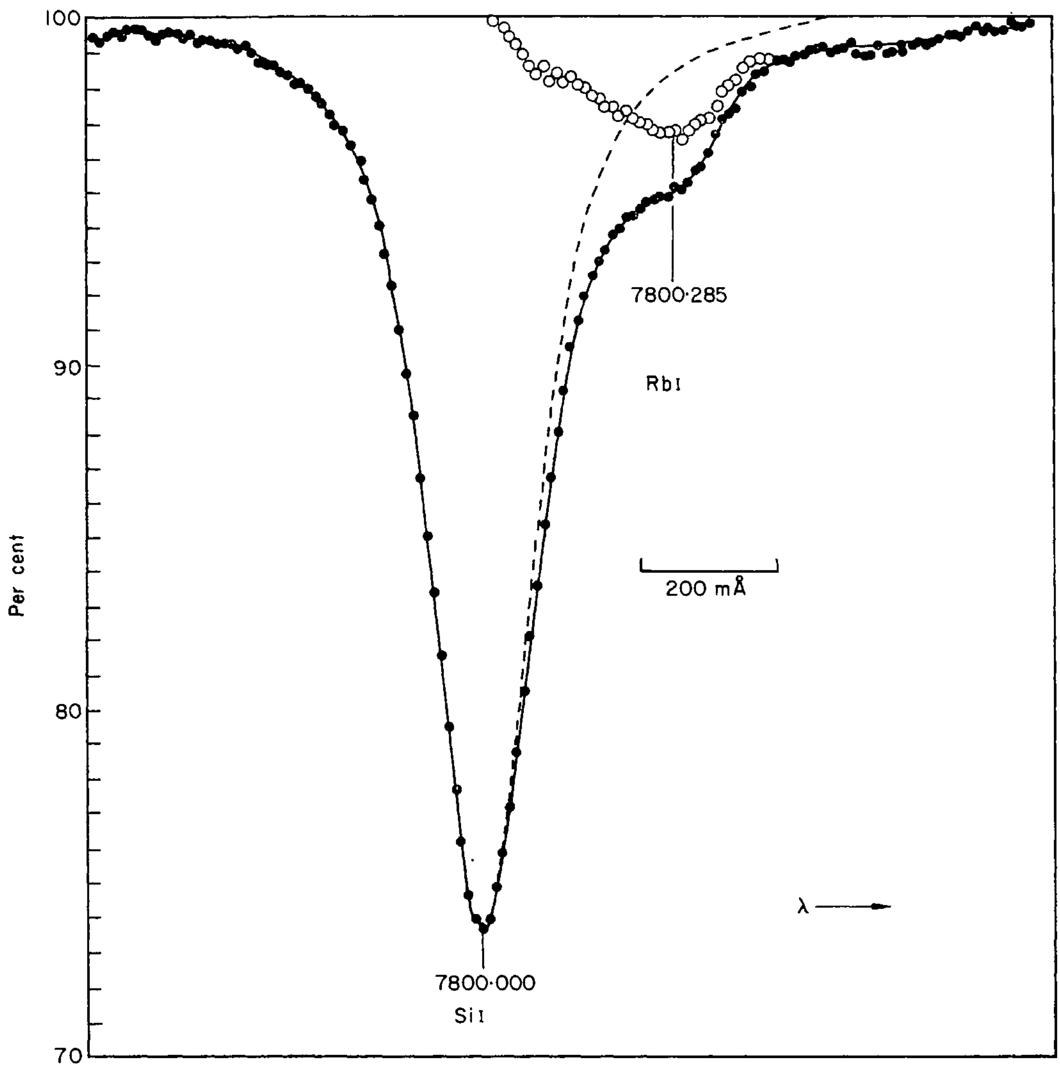


FIG. 1. *A low noise scan of the Si I–Rb I blend at λ 7800. This scan was obtained with the entrance slit of the spectrometer positioned at the centre of the solar disk. The profile for the Rb I line is shown by the open circles and is obtained by a subtraction of the reflected blue wing (dashed line) from the observed red wing. This simple method yields the true profile for the weaker Rb I line except close to the centre of the Si I line.*

the water vapour line as other (weak) lines appeared to be present in this wing. Instead, an analytical profile was fitted to the line core and extrapolated to obtain the wing. A gaussian profile provides a slightly better fit to the core than a dispersion profile (see Fig. 4). The resulting Rb I line profile is shown in Fig. 4.

The use of a dispersion profile results in an observed profile for the Rb I line which is double peaked and bears little resemblance to the predicted profile.

The observed wavelength for the Rb I line is estimated to be 7947·561 Å. The predicted wavelength is 7947·581 Å. This latter value is derived from the laboratory measurements by addition of the gravitational redshift and the doppler shift arising from solar rotation. In view of the blended condition of the line, the difference of 20 mÅ between the predicted and observed wavelengths is probably not serious; it is less than twice the estimated probable error.

A synthetic profile was fitted to the Rb I line in the same manner as was done for λ 7800. The agreement with the observed profile is good (see Fig. 4). From the fitted profile the equivalent width of λ 7947 is 5·2 ± 0·8 mÅ. The uncertainty is based on the scatter between three different measurements.

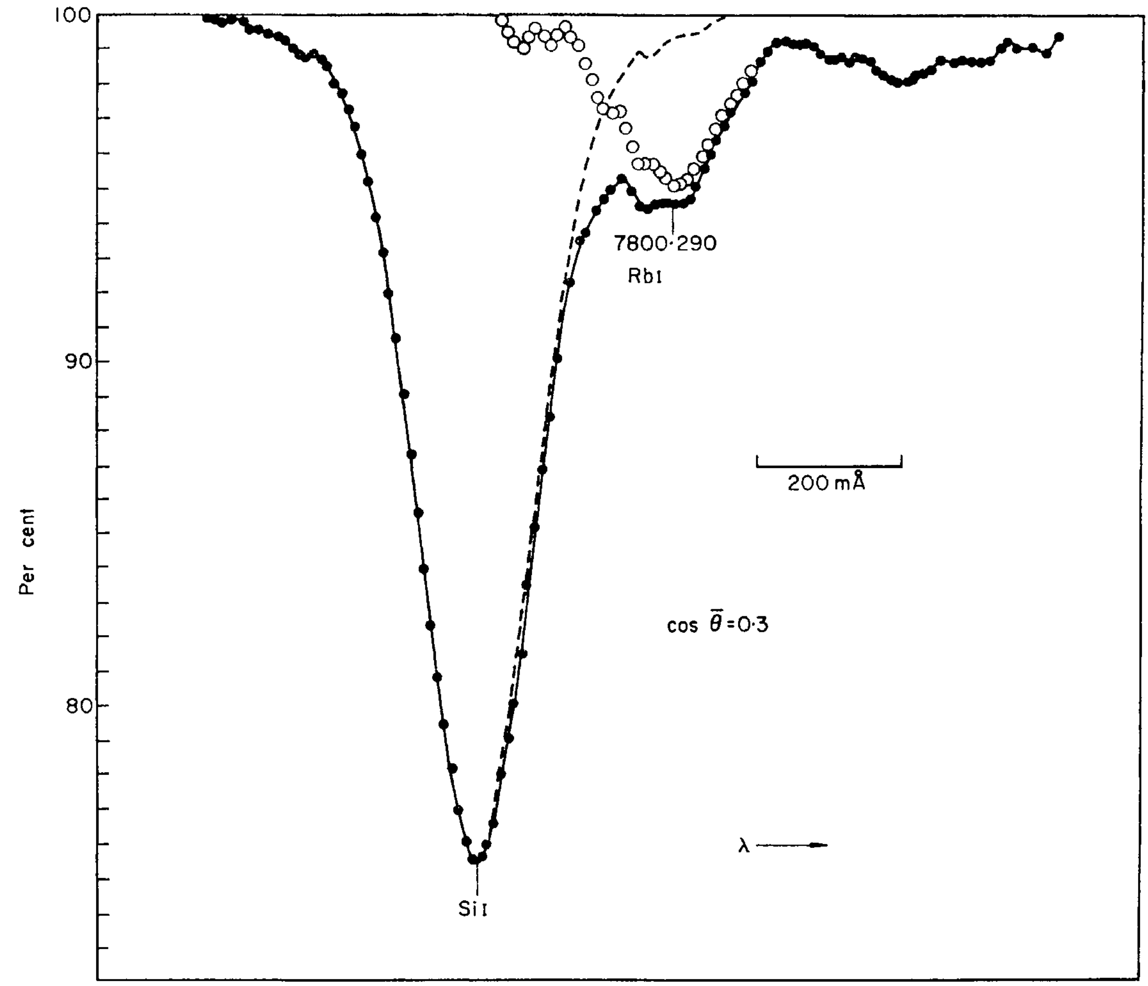


FIG. 2. *A low noise scan of the Si I–Rb I blend at λ 7800 obtained for the disk position* cos θ = 0·3. *The Rb I line (open circles) is stronger than in the spectra obtained for the centre of the disk.*

3. *Oscillator strengths.* The oscillator strengths for the resonance doublet were recently determined from an accurate lifetime measurement (Link 1966). The results

$$^2S_{1/2}\text{–}^2P^\circ{}_{3/2}f = 0{\cdot}675 \pm 0{\cdot}013$$
$$^2S_{1/2}\text{–}^2P^\circ{}_{1/2}f = 0{\cdot}335 \pm 0{\cdot}006$$

are in excellent agreement with the results obtained by Stephenson (1951) from a magneto-rotation experiment and which were adopted by GMA for their discussion of the rubidium abundance. The above results are more precise and are adopted for the present discussion.

4. *Abundance.* The model atmosphere of Lambert (1967) was adopted. The equivalent widths of $\lambda$ 7800 at the centre and limb and the equivalent width of $\lambda$ 7947 at the limb give the following abundances:

$$\log N(\mathrm{Rb}) = 2{\cdot}51 \pm 0{\cdot}05 \ \lambda\, 7800, \text{ centre}$$
$$2{\cdot}64 \pm 0{\cdot}07 \ \lambda\, 7800, \text{ limb}$$
$$2{\cdot}71 \pm 0{\cdot}10 \ \lambda\, 7947, \text{ limb.}$$

The difference between the first two values is a consequence of the failure of the model to predict correctly the observed centre–limb variation. For the ratio $W_\lambda(\cos\theta = 0{\cdot}3)/W_\lambda(\cos\theta = 1)$, the model predicts a value of 1·3 which is to be compared with the observed ratio of 1·7 ± 0·4. Use of a three-stream model atmosphere (Withbroe 1967) only made matters worse as the predicted value was 1·12.

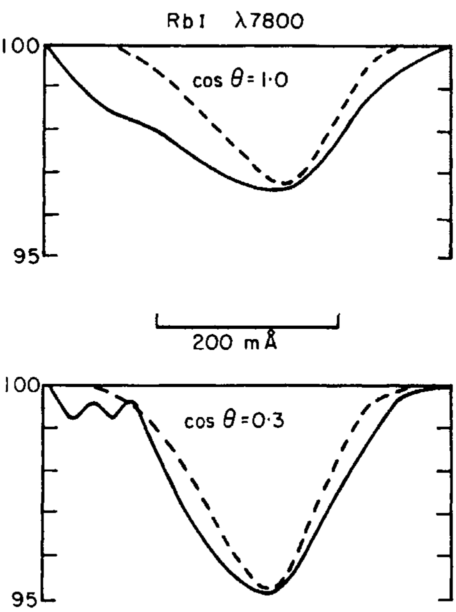


FIG. 3. *The observed line profile for the Rb I resonance line at* 7800 Å, *which is taken from Figs* 1 *and* 2 *and is given by the solid line, is compared with a predicted line profile (dashed line), which is computed from the known hyperfine structure, an isotopic ratio equal to the terrestrial value and a model solar atmosphere. The close similarities between the observed and predicted line profiles for the disk position* $\cos\theta = 0{\cdot}3$ *are to be noted.*

The correct explanation for the observed centre–limb variation is unknown. However, in the following section the suggestion is made that the method of reduction may result in an under-estimate of the equivalent width at the centre of the disk. In view of the superior fit to the observed profile in the $\lambda$ 7800 limb spectra, double weight is given to the abundance derived from these spectra. The mean abundance is therefore

$$\log N(\mathrm{Rb}) = 2{\cdot}63.$$

The uncertainty in the abundance estimate is put at about ± 0·10, and includes an estimate for the effect of model atmosphere uncertainties.

The isotopic composition of rubidium cannot be determined with any certainty. Although the noise level of the present scans is satisfactorily low, the blending of both resonance lines is the limiting factor. However, there can be little doubt that both $Rb^{85}$ and $Rb^{87}$ are present as the $\lambda$ 7800 profile at $\cos\theta = 0{\cdot}3$ (Fig. 3) demonstrates. The most probable conclusion is that the solar and terrestrial isotope ratios are identical. In the spectrum of a sunspot, the Si I line is weakened and the Rb I resonance line considerably enhanced. A careful study of this blend using photoelectric scans of sunspot spectra may permit an evaluation of the isotope ratio.

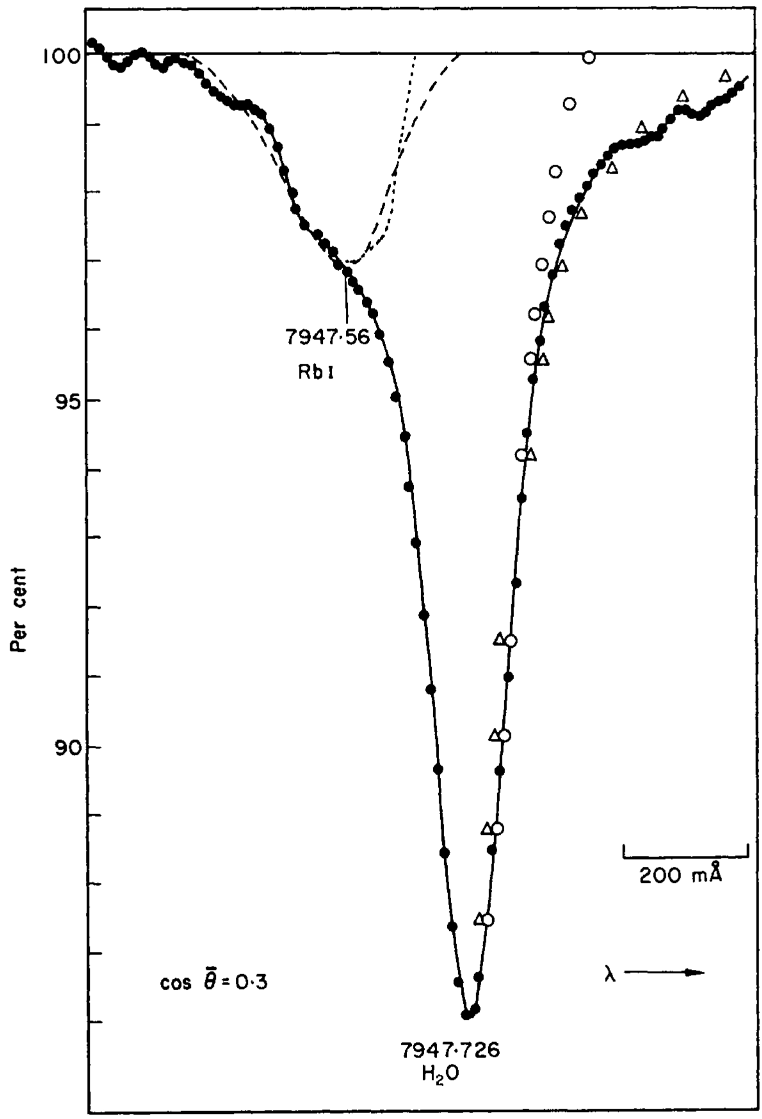


FIG. 4. *A low noise scan of the weaker Rb I resonance line at 7947 Å. This line is blended with a stronger $H_2O$ line. A partial separation of the line is shown in this scan, which was obtained near the east limb at* cos $\theta$ = 0·3. *The observed profile (dotted line) for the Rb I line is obtained by the reflection and subtraction of the red wing of the $H_2O$ line as represented by the best fitting gaussian (open circles). The open triangles denote the best fitting dispersion profile (see text for full discussion). The predicted line profile is shown by the dashed line.*

5. *Discussion.* The Rb I profiles at λ 7800 were obtained on the assumption that the Si I line has no intrinsic asymmetry. This assumption may be invalid. In this section, two possible sources of asymmetry are considered.

Profiles of medium strong Fraunhofer lines are observed to be asymmetric (e.g. Olson 1962). The line depth is greater over the blue half of the profile except in the far wings, where the asymmetry is reversed. The interpretation of these asymmetries in terms of a convective velocity field (de Jager & Neven 1967), appears to be valid. An assumption of symmetry will, in the presence of a strengthened blue wing, result in an underestimate for the equivalent width of the Rb I line. Furthermore, if the convective motion is primarily vertical, the asymmetry should diminish towards the limb. This would be consistent with the improved fit to the theoretical Rb I line profile obtained with the limb spectra.

Observations of the Si I line at 5665 Å have been obtained. This line has an excitation potential and equivalent width quite similar to λ 7800. At the centre of the disk, there is a weak blue asymmetry in the core and a stronger red asymmetry in the wings; at the limb, the red asymmetry remains but the core is symmetrical. These features are only slightly modified when a correction is made for the instrumental profile. If the observed core asymmetry were present in λ 7800, the assumption of a symmetric profile would reduce by about 0·7 mÅ the equivalent width of the Rb I line, which is derived by the subtraction procedure. This would be partially counteracted by the red asymmetry in the wings. However, the red asymmetry observed in λ 5665 seems a little too strong to be accounted for by convection only. Weak blends are probably responsible.

The assumption of a symmetric profile for the Si I line appears to be valid for a reduction of the limb spectra. The close similarities between the observed and predicted Rb I profiles supports this statement. For the spectra at the centre of the disk, the assumption is probably responsible for a slight underestimate of the true equivalent width. The probable increase is about 0·5 mÅ over the results given in Section 2.1 and corresponds to a reduction in the observed centre–limb ratio for the equivalent width to $1\cdot5 \pm 0\cdot3$, which is in approximate agreement with the model atmosphere prediction.

In the centre spectra there is some evidence for a weak line between the Rb I line and the peak of the Si I line. The observed Rb I profile, which is obtained on the assumption that the Si I line is symmetrical, has a marked blue asymmetry, which cannot be attributed to a Rb I component and which is unlikely to be wholly attributable to the asymmetry of the Si I line resulting from convective motions. It is proposed that there is some evidence in the centre spectra for a weak line between the Rb I and Si I lines. The observations, which were obtained over a range in zenith distance, rule out the possibility of a weak terrestrial line at this position. Available sources of laboratory wavelengths were consulted without success. The possibility that the line belongs to the CN red system cannot be excluded because present wavelength lists are incomplete, but the observation that it is weakened towards the limb is evidence against this identification. The possibility was examined that this unidentified line may be a blend of the isotopic lines from $Si^{29}$ and $Si^{30}$, which have terrestrial abundances of 4·7 and 3·1 per cent respectively. Unfortunately, isotopic shifts have not been measured for this line. Measurements of ultraviolet lines for the $Si^{28}$ and $Si^{30}$ isotopes (Holmes & Hoover 1962) indicate specific shifts of about $\pm 0\cdot06$ cm$^{-1}$ in addition to the normal mass effect shift. Therefore, the presence of isotopic lines in the red flank of λ 7800 cannot be ruled out *a priori*. The following preliminary calculation indicates that the suggested identification is probably correct: if the two isotopic lines are assumed to be coincident in wavelength and situated 40 mÅ (0·07 cm$^{-1}$) to the red of the $Si^{28}$ line peak, the additional absorption at this position amounts to 3 per cent of continuum. This would be ample to account for the extended blue wing to the Rb I line profile and for its weakening from centre to limb.

6. *Concluding remarks.* The present study was undertaken because of an awareness that an improved estimate for the rubidium abundance should be obtainable through the use of equivalent widths derived from scans obtained with the Oxford photo-electric spectrometer. The attempt was successful and the rubidium abundance is now more firmly established. Perhaps more important than this result are the supplementary results.

A cursory inspection of the scans indicates that a more detailed analysis of the Rb I profiles would be possible if they were observed as isolated Fraunhofer lines; for example, the quality of the scans would permit an evaluation of the $Rb^{85}$ to $Rb^{87}$ isotope ratio. The present analysis of the Rb I–Si I blend is limited by uncertainties concerning the Si I line profile. A comprehensive series of observations of Fraunhofer lines should be undertaken in order to determine the extent of their asymmetry. The interpretation of the asymmetries in terms of convective motions appears to be substantially correct. An additional asymmetry may result from isotopic lines. It would be of considerable interest to study unblended lines of Si I (and other species) and to attempt an evaluation of the isotopic abundances in the solar photosphere.

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