EUROPIUM AND LANTHANUM IN SUNSPOT AND IN THE UNDISTURBED PHOTOSPHERE

G. BACHMANN, K. PFLUG, and J. STAUDE

Zentralinstitut für solar-terrestrische Physik (HHI),
Sonnenobservatorium Einsteinturm, Potsdam, D.D.R.

(Received 26 June, 1970)

Abstract. Line profiles of Eu II λ4129.7 Å and La II λ4086.7 Å were observed photoelectrically and photographically in the photosphere and within sunspots and after correction were compared with calculated profiles. The observed large hyperfine structure broadening and isotope shift of λ4129.7 Å confirm the Eu origin of this line and suggest a larger Eu abundance than that recently published by Grevesse and Blanquet (1969). The line profiles within the spot may be well represented by means of the spot model of Hénoux (1969), while older spot models are not able to do it. An abundance difference between spot and photosphere has not been observed.

1. Introduction

In the spectra of magnetic stars lines of elements like Cr, Mn and some rare earths, especially Eu, are unusually strengthened. It is well known that the observations are showing temporal variations of the strengths of these lines, which are correlated with the magnetic field.

This effect can be interpreted by anomalous abundances of the corresponding elements in the surface layers of magnetic stars depending on the magnetic field strength. As one possibility of interpretation of these facts Babcock (1963) suggested a diffusion mechanism, which may result in a concentration of the corresponding elements in the surface of the star. This mechanism does only work, if there exists a large gradient of the magnetic field and if the atoms have a large magnetic momentum and spherical symmetry in the ground state.

It is of interest to investigate the behaviour of rare earths, especially Europium, in strong solar magnetic fields, although Babcock assumed that the gradient of the magnetic field strength in sunspots is hundred times smaller than necessary for the diffusion mechanism. In this analysis we investigated the lines Eu II λ4129.7 Å and La II λ4086.7 Å in the undisturbed photosphere and in sunspots in view of a possible anomalous behaviour of the abundances of rare earths in sunspots.

The line Eu II λ4129.7 Å corresponding to the conditions mentioned above can be well observed in the solar spectrum and shows also in magnetic stars the specified anomalies. For comparison we used the line La II λ4086.7 Å. Lanthanum has very similar excitation and ionisation potentials and atomic weight like Europium, but does not fulfil the conditions for the diffusion mechanism.

Additional results of the present investigation refer firstly to the correct interpretation of the observed line contour (Eu II λ4129.7 Å) by hyperfine structure broadening

Solar Physics **15** (1970) 113–119. *All Rights Reserved*

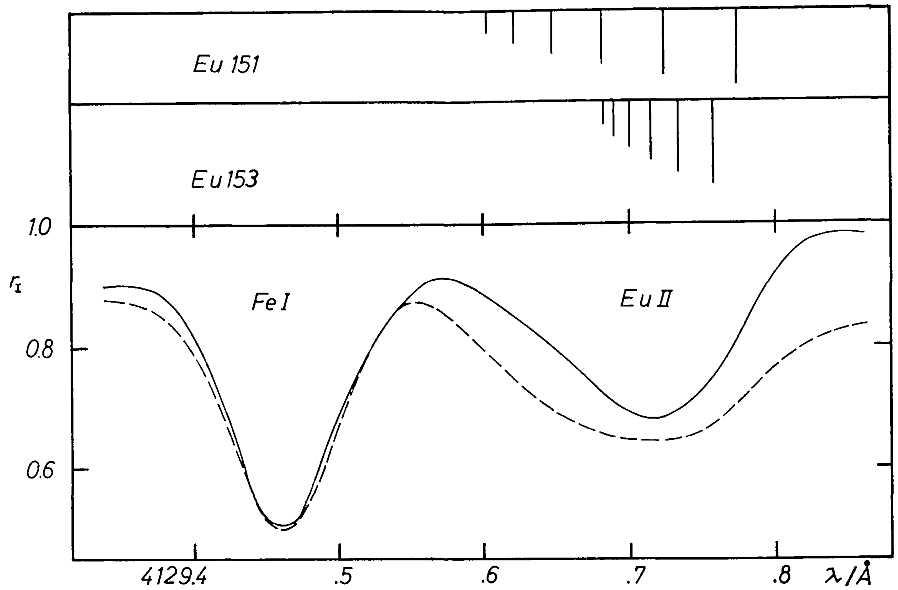

Fig. 1. Photoelectric observations of the line Eu II λ 4129.7 Å in spot and photosphere (dashed and full line, respectively); uncorrected as to apparatus function and scattered light, but mean profiles from 5 and 6 observations, respectively. The scale of abscissae is fixed approximately to the neighbouring Fe I line. cos $\vartheta = 0.866$; $H = 3300$ G in the spot. The pattern above the line profiles indicates the hfs splitting of the Eu isotopes.

and isotope shift and secondly to the determination of solar abundances of Lanthanum and Europium.

2. Observations

The present analysis is based on photographic as well as on photoelectric observations of the lines Eu II λ4129.7 Å, La II λ4086.7 Å and Fe II λ4128.7 Å (the latter for discussion of scattered light) performed at the Einstein tower. We used the second order of the grating spectrograph, which gives a dispersion of 1.5 mm/Å and a resolving power $\lambda/\Delta\lambda$ of about 10^5. The diameter of the solar image was about 13 cm in the case of photographic and about 26 cm in the case of photoelectric observations. The photographic observations consist of 7 sets of spectrograms each of them containing 3 to 5 expositions showing a spot spectrum surrounded by spectra of the photosphere. The line profiles derived from different spectrograms but belonging to the same spot are joined together to a mean profile. Deviations between the profiles of different spots are small, because we only used large spots near the centre of the disc. So it is justified to use a mean profile of all observations for the following discussion. The accuracy of the mean profiles may be characterized by a mean error of 1.1%.

The photoelectric measurements were carried out by means of a two-channel photometer which largely compensates the fluctuations caused by seeing. For the undisturbed photosphere the mean error in intensities is about 0.5%. The comparison of our profiles with the *Utrecht Atlas* (Minnaert *et al.*, 1940) and the recent measurements of equivalent widths by Moore *et al.* (1966) yields a good agreement.

Because of the much higher difficulties arising in photoelectric photometry of spot spectra, we got 5 profiles only for each of the lines Eu II λ4129.7 Å and Fe II λ4128.7 Å. The umbra was selected by a circular diaphragm of 1–2 mm diameter, which corresponds to 7–15 sec of arc. It is evident that the accuracy of the measurements in spots is lower than in the photosphere. But the elimination of the photospheric light by means of small diaphragms depresses considerably the scattered light in the spectrograph and gives in this way a higher accuracy for the photoelectric measurements.

3. Correction of the Observed Line Profiles

Corrections because of scattering and blurring in the earth atmosphere are only necessary for spot profiles; for photospheric profiles they are negligible. By means of formulae given by Kneer and Mattig (1968) and by David and Elste (1962) for one of the observed spots we calculated the corrections due to scattering in the earth atmosphere for the central intensity of La II λ4086.7 Å in the centre of the umbra. The correction diminished the central intensity of this line by 2%.

By Zwaan (1965) it was shown that the corrections due to blurring of the umbra continuum, especially for small spots, may be considerable. If the results by Zwaan were correct, then on conditions of mean blurring only the umbral intensities of spots with diameters larger than 20 seconds of arc should remain unadulterated.

In the present analysis we tried to calculate the corrections due to blurring and scattering assuming the intensity ratio spot-photosphere and the true equivalent width of Fe II λ4128.7 Å to be equal for all large spots. If the corrected ratio of the equivalent widths in spot and photosphere of this line given by Fricke and Elsässer (1965) is the true one, we are able to calculate the stray light in our spectrograms by means of the formula

$$r_\lambda^s = \bar{r}_\lambda^s - \frac{\alpha}{\varphi_\lambda}(r_\lambda^p - r_\lambda^s).$$

Here r_λ^s and r_λ^p are the true depressions of the line in spot and photosphere respectively; $\bar{r}_\lambda^s$ is the depression measured, α is the portion of stray light and φ_λ the true intensity ratio spot-photosphere. We obtained the same equivalent width of Fe II λ4128.7 Å as Fricke and Elsässer assuming α to be 13% for the photographic and 9% for the photoelectric observations. With these values for α we calculated the corrections for the Eu II and the La II line. The central intensity of these lines is then diminished by 2 to 3% due to the combined effect of scattering and blurring. Having in mind the correction mentioned above this result supports the conclusion that in our case the spot profiles are not disturbed by blurring but only by scattering.

The scattered light caused by the telescope was investigated in conjunction with the atmospheric scattered light.

The main portion of scattered light within the spectrograph (ca. 1%) is due to ghosts, a smaller portion (ca. 0.3%) to reflection and scattering at the optical surfaces of the spectrograph. For both portions of scattered light the profiles were corrected. Moreover, the line profiles have to be corrected because of distortion by the horizontal instrumental profile of the spectrograph. For that we applied the method of Voigt profiles given by Elste (1953).

4. Computation of Theoretical Line Profiles

For interpretation the line profiles were compared with model calculations for the investigated lines. The computer programs, having been described in more detail in another paper (Staude, 1970), assume LTE and may take into account arbitrary model atmospheres and anomalous Zeeman splittings. The model atmospheres used for the calculations were the photospheric model 'BCA' (Gingerich and de Jager, 1968) and five different spot models: Fricke and Elsässer (1965), Zwaan (1965), Hénoux (1969) and models No. 3 and No. 7 from a set of 9 hydrostatic spot models by Stankiewicz (1968/1969). The absorption coefficients have been taken from Bode (1965), the partition functions from other publications like Corliss and Bozman (1962) and Aller (1963), the *gf* values from Corliss and Bozman (1962).

The microturbulence ξ_{tu} and the line constants $gf\varepsilon$ (product of statistical weight of the lower energy level, oscillator strength and abundance of the element) have been determined by fitting the calculated line profiles for the BCA to the observed ones of the photosphere after correction. Then the same constants were used to calculate magnetic splitted profiles for the spot models in order to compare them with the observed ones of the spot.

Because of the complicated structure of the blue wing of the Eu line only the red wing was used for the fitting. We obtained the abnormally large value $\xi_{tu}=5$ km/sec; the value $\xi_{tu}=2.7$ km/sec for the La line also exceeds the usual values of the microturbulence.

5. Discussion of the Results

5.1. Hyperfine structure and isotope shift of Eu II λ4129.7 Å

The observed strong broadening and asymmetry of the Eu line may be explained by the hyperfine structure (hfs) splitting and isotope shift of the two stable Europium isotopes Eu 151 and Eu 153 (Krebs and Winkler, 1960; Guthöhrlein, 1968; see Figure 1). Moore *et al.* (1966) have ascribed the weak line within the blue wing of the main line to a blend of unknown origin. But analogous to the analysis of other Eu II lines with similar hfs pattern just now published by Hauge (1970) the weak line must be attributed only to the larger splitted Eu 151 while the main line component is formed by both isotopes. Probably the La line is also somewhat broadened by hfs.

5.2. Photospheric abundances

In spite of possible gross errors arising from abundance determinations from one line only (uncertainties of the *gf* values!), it seems that some conclusions may be drawn from our observations. Older abundance determinations for Eu (Righini and Rigutti, 1966; Wallerstein, 1966) and La (Wallerstein, 1966) are somewhat dubious because of their simple methods and the fact that many of the used lines are now known to be blended (new Utrecht catalogue: Moore *et al.*, 1966). Recently, more exact determinations have been published by Grevesse and Blanquet (1969), their result for the line La II 4086.7 Å coincides well with our value. For Eu, however, they have selected some lines which yield small abundances, while four other lines (e.g. λ4129.7) were eliminated and suspected to be only partly due to Eu II. But the selected lines are situated in the wings of strong neighbouring lines and are therefore influenced by blend effects too: While the measured equivalent widths coincide well with those of the Utrecht catalogue (reduction by simple product rule), there exist large discrepancies with the reduced widths of the catalogue (approximate regard of the blend effect) up to factors like 2.5, 4 and 6! Thus, the abundances from these lines may be underestimated. On the other hand, however, the good accordance between the observed and the theoretically expected hfs broadening and isotope shift of the line λ4129.7 Å seems to refute the doubts of Grevesse and Blanquet concerning the Eu origin of this line. Summarizing we may conclude that the Eu abundance by Grevesse and Blanquet ($\log \varepsilon = 0.49$) may be too small; therefore we trust more on our value $\log \varepsilon = 1.0$ although it comes from one line only. Our value coincides better with the older determinations where perhaps some different errors have compensated each other.

5.3. Behaviour of the lines within the spots

The studied lines are very sensitive with respect to the temperatures and their gradients. Thus the calculations show strong intensifications of the line profiles within the spot

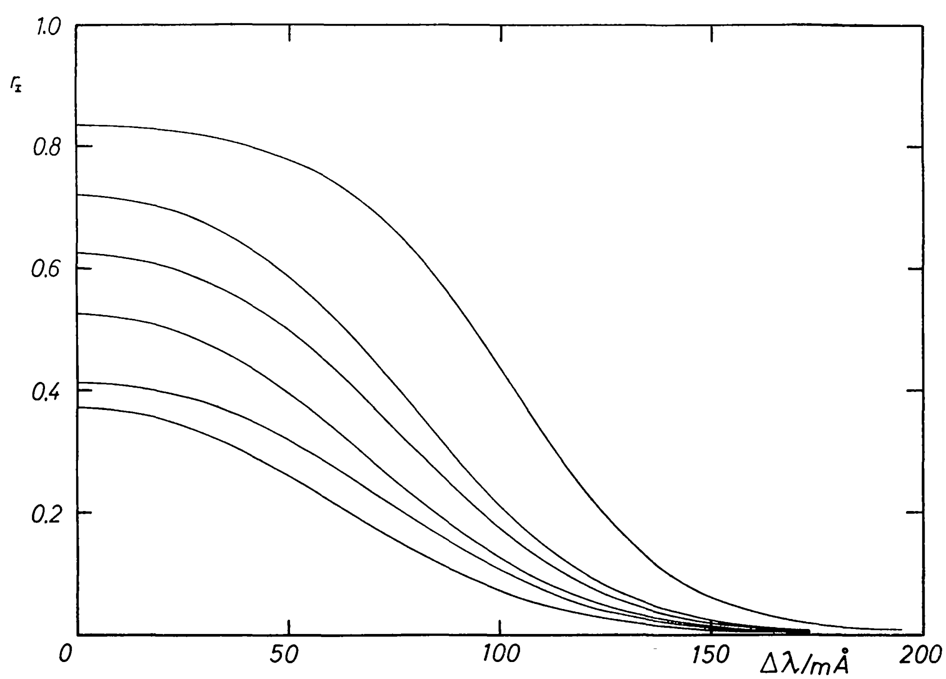

Fig. 2. Theoretical line profiles (red wing of Eu II λ 4129.7 Å) for different model atmospheres, $\cos\vartheta = 1$, $H = 0$ G. The profiles from above to below within the line core are calculated for the spot models of Fricke – Elsässer, Zwaan, Nos. 3 and 7 of Stankiewicz, Hénoux and the photospheric model BCA.

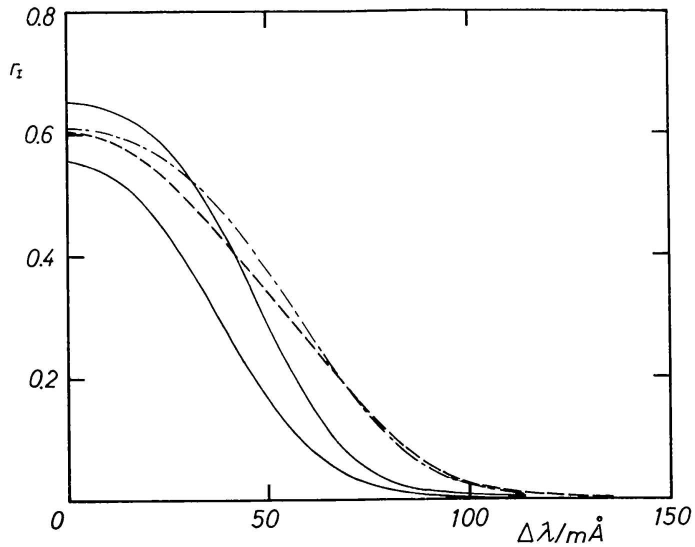

Fig. 3. Effect of magnetic splitting on the line La II λ 4086.7 Å, $\cos\vartheta = 0.866$. From above to below in the line core: model Hénoux, $H = 0$; $H = 3300$ G for $\psi = 60°$ and $30°$; model BCA, $H = 0$.

models (Figure 2). The broadenings by magnetic splitting are less effective (see Figure 3).

The older spot models (Fricke and Elsässer, 1965; Zwaan, 1965), however, produce too large line profiles compared with the observed ones; this is mainly caused by the large temperature gradients of these models. The line contours calculated for the spot models of Stankiewicz coincide better with the observations. The best accordance is obtained, however, by means of the spot model of Hénoux (1969), which has a very flat temperature gradient.

Taking into account the influence of scattered light we may conclude that no differences of the abundances of Eu and La between spot and photosphere are traceable.

Acknowledgement

We wish to thank Professor F. W. Jäger for the suggestion and stimulation of this work, for handing over own photographic spectrograms and critical reading of the manuscript.

References

Aller, L. H.: 1963, *Astrophysics. The Atmospheres of the Sun and Stars.* 2nd ed., Ronald Press, New York.
Babcock, H. W.: 1963, *Astrophys. J.* **137**, 690.
Bode, G.: 1965, *Die kontinuierliche Absorption von Sternatmosphären in Abhängigkeit von Druck, Temperatur und Elementhäufigkeit.* Inst. Theoret. Phys. Univ. Kiel.
Corliss, C. H. and Bozman, W. R.: 1962, Nat. Bur. Stand. Monograph 53, Washington.
David, K. H. and Elste, G.: 1962, *Z. Astrophys.* **54**, 22.
Elste, G.: 1953, *Z. Astrophys.* **33**, 39.
Fricke, K. and Elsässer, H.: 1965, *Z. Astrophys.* **63**, 35.
Gingerich, O. and de Jager, C.: 1968, *Solar Phys.* **3**, 5.
Grevesse, N. and Blanquet, G.: 1969, *Solar Phys.* **8**, 5.

Guthöhrlein, G.: 1968, *Z. Phys.* **214**, 332.
Hagedorn, H.: 1964, *Publ. Astrophys. Observ. Potsdam* **104**, B3.
Hauge, Ö.: 1970, *Solar Phys.* **11**, 17.
Hénoux, J.-C.: 1969, *Astron. Astrophys.* **2**, 288.
Holweger, H.: 1967, *Z. Astrophys.* **65**, 365.
Kneer, F. and Mattig, W.: 1968, *Solar Phys.* **5**, 42.
Krebs, K. and Winkler, R.: 1960, *Z. Phys.* **160**, 320.
Minnaert, M., Mulders, G. F. W., and Houtgast, J.: 1940, *Photometric Atlas of the Solar Spectrum*, D. Schnabel, Amsterdam.
Moore, C. E., Minnaert, M. G. J., and Houtgast, J.: 1966, *The Solar Spectrum* 2935 Å *to* 8770 Å, Nat. Bur. Stand. Monograph 61, Washington.
Righini, A. and Rigutti, M.: 1966, *Ann. Astrophys.* **29**, 379.
Stankiewicz, A.: 1968, paper presented at the 5th Consultation on Heliophysics and Hydromagnetics in Potsdam, 1969, *Geod. Geophys. Veröff.*, Ser. II, No. 13, 7.
Staude, J.: 1970, *Solar Phys.* **12**, 84.
Unsöld, A.: 1955, *Physik der Sternatmosphären*, 2nd ed., Springer, Berlin.
Wallerstein, G.: 1966, *Icarus* **5**, 75.
Zwaan, C.: 1965, *Rech. Astron. Observ. Utrecht* **17**/4.