is $dP/dT = 1140$ atm/deg.

The change of entropy $\Delta S$ and of molar volume $\Delta V$ upon transformation can be derived from the Clausius-Clapeyron equation using the experimentally determined values of $dP/dT$, $L$, and $T_{\text{tr}}$. This gives $\Delta S = 0.0041$ cal/mole deg, and $\Delta V = 1.4_8 \times 10^{-4}$ cm$^3$/mole. $\Delta V$ constitutes $1.2_7 \times 10^{-3}$% of the molar volume.

It may be added that the corresponding transition in solid He$^4$ ($\alpha$He$^4$ -$\beta$He$^4$) has also been observed in a previous experiment with this apparatus. The transition occurred at 14.99°K for a sample of molar volume 11.77 cm$^3$/mole. The latent heat of transition was 0.060 cal/mole.

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# PRECISE OBSERVATION OF THE PROFILE OF THE FRAUNHOFER STRONTIUM RESONANCE LINE. EVIDENCE FOR THE GRAVITATIONAL RED SHIFT ON THE SUN

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We wish to report a measurement of the profile of the solar strontium resonance line $^1P_1 - {}^1S_0$, 4607.3 A, by a method permitting high resolution. Observation of this profile on the limb of the Sun as well as the center of the disk permits an unambiguous separation of wavelength shifts caused by mass motion on the Sun and the gravitational red shift. The shift attributable to the relativistic effect is found to be very close to the theoretical value. The success of this observation of the red shift is due to the fact that in this experiment atoms are used as a clock both on the Sun and the Earth. This removes errors made in wavelength calibration.

In our method of spectroscopic analysis the light to be analyzed excites the optical resonance of the vapor of a metal. The intensity of the light reemitted by the vapor, proportional to the incident intensity, is measured at right angles to the exciting beam by a photomultiplier. The scattering frequency is shifted by applying a magnetic field to the vapor. The variation in intensity of the reemitted light as a function of the field gives the profile of the exciting light. We have used this method on the $D$ lines of sodium of the twilight glow,[1] the study of sources in the laboratory,[2] the fluorescence of the Moon and Venus,[3] and the detection of the dayglow.[4]

In order to study the profile, it is necessary to use only one component (through a circular analyzer) of a resonance line with normal Zeeman effect and without hyperfine structure. We have operated on an atomic beam of strontium in order to minimize the width of the absorption line. This beam and the discussion of its use on solar light have been discussed earlier.[5]

The strontium (Fig. 1) is placed in a steel vessel heated to 600°C in a silica tube, water-cooled at the end. Two diaphragms delimit the beam whose half-aperture ratio is $\frac{1}{20}$. The metal beam passes through an observation chamber where it is excited by a light beam of half-aperture-angle $\frac{1}{20}$. The excitation can be caused by a white light source or by the light coming from an image of the Sun, of diameter 11 cm, formed by an objective of 30-cm diameter. The angle used on the Sun varies from 30″ to 1′. A mirror is used to observe the light emitted parallel to the magnetic axis; the half-angle of observation is $\frac{1}{10}$ in order to remove mixing with $\pi$ components. Stray light is measured with the metal beam turned off. The ratio of intensity of stray light to resonance light is 1 to 3; of resonance light to noise, 20 to 1.

The beam geometry is such that the Doppler

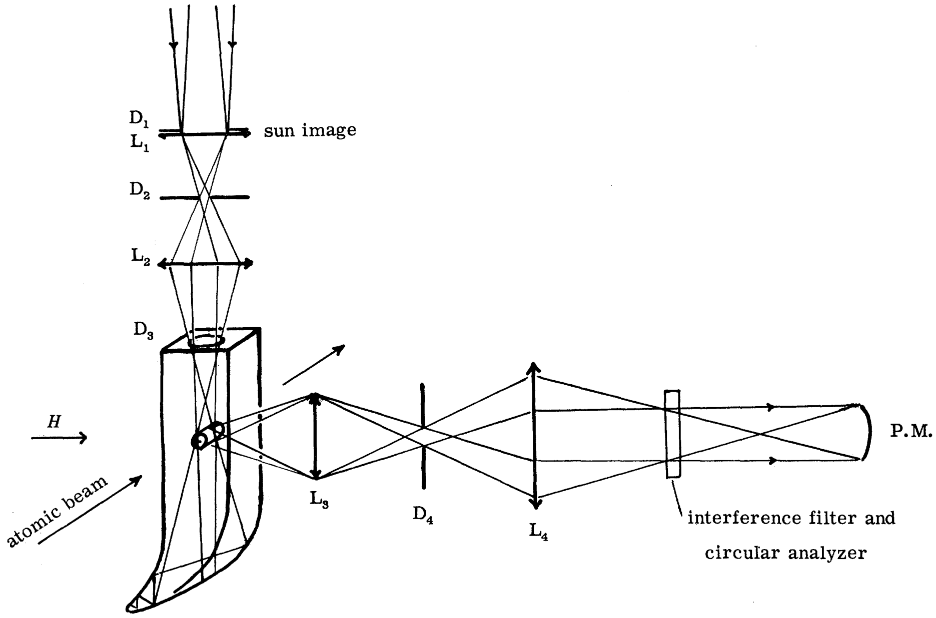

FIG. 1. Schematic diagram of the experiment. $D_1$: diaphragm defining a part of the solar image; $D_2$, $D_3$, $D_4$: diaphragms removing the stray light; $L_1$, $L_2$, $L_3$, $L_4$: converging lenses.

shape of the absorption line has a theoretical width of $8\times10^{-4}$ A. But at an oven temperature of 550°C and above, the width of the profile is increased to $10^{-3}$ A at 550°C and $2\times10^{-3}$ A at 640°C by self-absorption of the light in the dense beam. We have traced a curve of growth (re-emitted energy as a function of the beam density for white light excitation) and conclude that at our temperature we explore the solar spectrum with a saturated profile of $(1 \text{ to } 2)\times10^{-3}$ A half-width.

When the beam is excited by a white source, the intensity re-emitted would be invariant with the field if the beam were optically thin. This is not the case and because of multiple scattering effects which we have discussed elsewhere,[4] the intensity varies with the field. The response of the beam has to be calibrated with a white light source before any spectrum is taken. Solar observations have been corrected for this white light effect, measured in every experiment since it depends on the beam density. The order of magnitude of the effect is 5 to 10% for $10^4$ gauss.

At the <u>center</u> of the solar disk, the intensity at the line bottom is 40% of the continuum intensity, just reached at $10^4$ gauss, much less than the 60% indicated by the Utrecht Atlas. The line is strongly asymmetrical; the line shape varies from day to day due to observation of different solar regions, but the axis of the line (middle of horizontal chords) is extremely regular [Fig. 2(a)]. The indicated shifts towards the red are corrected for relative motions of the earth. Observed fluctuations around the given values can amount to $10^{-3}$ A. The theoretical value of the gravitational red shift is $9.76\times10^{-3}$ A. The observed shift at the bottom is very near the relativistic value.

At the <u>limb</u> of the solar disk (1′ of arc from the edge) the intensity at the bottom is 55% of the continuum intensity. The line axis has a completely different shape than at the center [Fig. 2(b)]. At the line bottom the axis stays vertical at a constant value shifted towards the red by $12\times10^{-3}$ A. This value finds a complete interpretation if we add to the mentioned relativistic shift the pressure red shift of the Lindholm effect. Lindholm's theory,[6] good enough for a resonance line, predicts a shift of $2.4\times10^{-3}$ A for the considered line with $T = 5700$°K and $10^{17}$ hydrogen atoms/cm$^3$. The theoretical red shift is thus $12.16\times10^{-3}$ A which is exactly the experimental value.

This means that at the center of the disk the measurements are affected by a third effect, a violet shift, which may be due to convective motions. This effect taking place at a certain depth is naturally displaced towards the continuum for the limb observations. If we superpose center and limb profiles, keeping the ratio of intensities constant, the two axes coincide on some interval. This asymmetry has been predicted by Schröter[7] in a model which reduces the photosphere to a mixture of hot ascending and cool descending currents whose speeds vary with altitude. The line

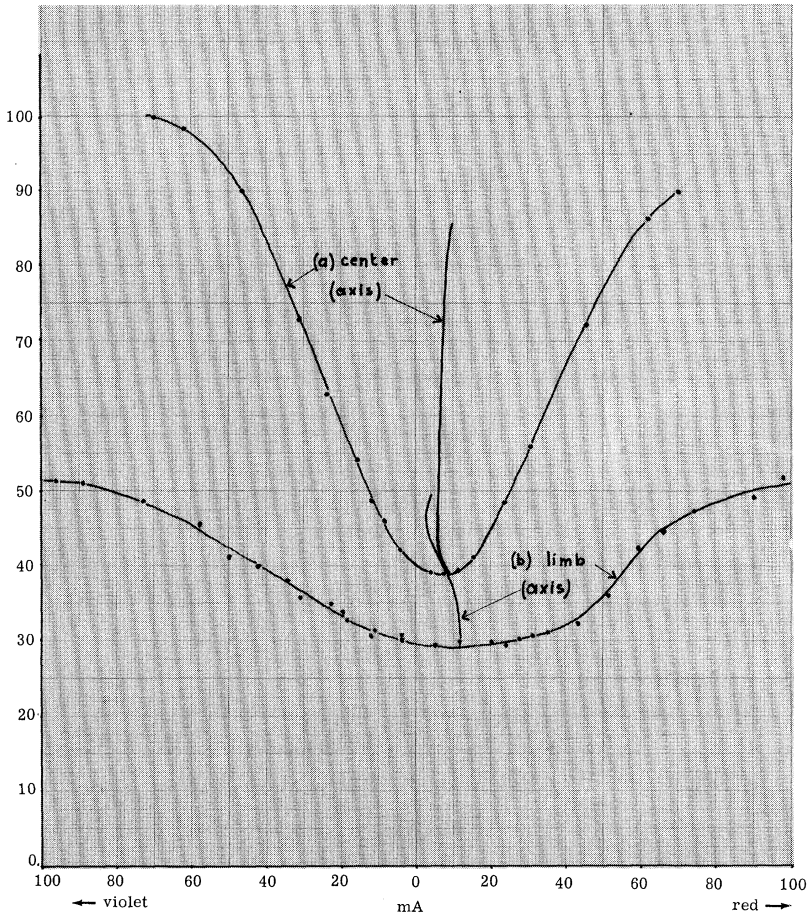

FIG. 2. Two profiles obtained August 5, 1961, between 16.00 and 17.00 U.T. (a) Center of the disk; (b) at 1′ from the limb.

shape of a group of spots has been obtained and exhibits elaborate structure due to Zeeman effect.

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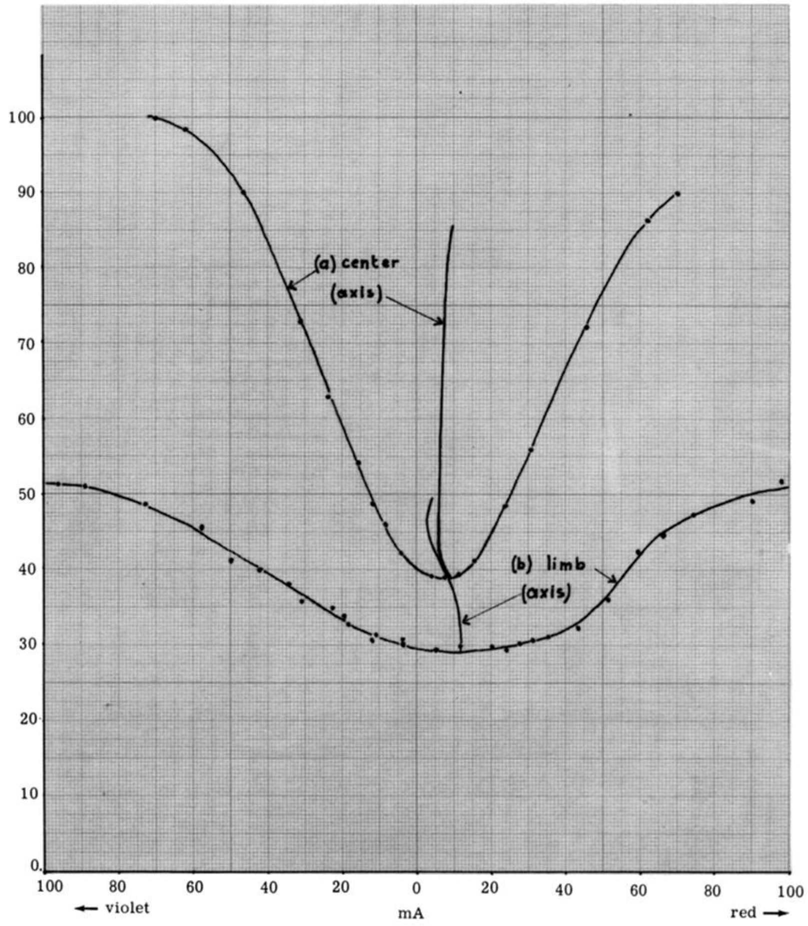

FIG. 2. Two profiles obtained August 5, 1961, between 16.00 and 17.00 U.T. (a) Center of the disk; (b) at 1′ from the limb.