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High Resolution Spectra of the Sun

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II. STARS

High resolution spectra of the Sun

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The University of Liège has operated, since 1958, a laboratory of solar spectroscopy at the International Scientific Station of the Jungfraujoch (Switzerland).

During recent years, much effort has been devoted in two main directions: (*a*) techniques of correction for the effects of the instrumental function to obtain the best possible knowledge of central intensities and profiles of photospheric lines; (*b*) increase of the signal to noise ratio in the records in order to detect and measure very faint absorption features.

In addition, a balloon-borne equipment is now under construction in Liège to observe, with maximum resolution, the near infrared solar spectrum from an altitude of about 80000 ft.

1. Introduction

The International Scientific Station of the Jungfraujoch, located in the Swiss Alps, at an altitude of 11 700 ft., is known as one of the best possible locations for the observation of the solar spectrum in the water-vapour absorption regions. That has been demonstrated by the work of M. Migeotte who published in 1956, in collaboration with L. Neven and J. Swensson, an atlas of the solar spectrum between 2·8 and 23·7 μm (Migeotte, Neven & Swensson 1956).

In 1958, the University of Liège installed at the Jungfraujoch a large prism-grating spectrometer especially designed for high-resolution solar spectroscopy. That instrument and the associated equipment have been described, in 1963, in the introduction of an atlas of the solar spectrum between 7500 and 12000 Å (Delbouille & Roland 1963).

Since 1963, efforts to improve the quality of the observations taken from the Jungfraujoch have been made to obtain a better accuracy in the determination of photospheric line profiles and an improvement of the signal/noise ratio.

In parallel with these problems, and in order to continue the Jungfraujoch work in the regions of the near infrared which remain inaccessible even from a high-altitude station, equipment has been designed and built to make balloon-borne observations of the solar spectrum.

We shall briefly discuss these three points.

2. Determination of line profiles and intensities

Further improvements of the models of the solar photosphere will only be possible on the basis of more accurate measurements of central-line intensities and of line profiles.

Two problems have in particular to be solved.

(a) *Effect of scattered light in the instrument*

The determination of central intensities is complicated by the fact that diffused light is nearly always present in the plane of the exit slit of the spectrometer.

We use the expression 'diffused light' in a large, general, sense. In fact, it is easy to distinguish between two different origins of such unwanted light reaching the detector.

First, radiation may be reflected or scattered by various internal parts of the spectrometer, with the exception of the grating itself. Use of very clean optics and limitation of the field of view of the detector by suitable diaphragms and screens can quite easily reduce that unwanted signal down to a low value. A proper way to measure the 'zero' line of the spectra will, in double-pass instruments, make it completely negligible (see below).

The second source of diffused light is the grating itself. Owing to imperfections of its surface and of its ruling, a grating is not only distributing the energy into the different geometrically well-defined orders, but, for each monochromatic incident radiation, a large number of ghosts and satellites are spread in between these intense maxima expected from the grating theory. The superposition of all these ghosts and satellites produced by the solar continuum in the vicinity of an absorption line can be considered, as far as its effect is concerned, as diffused light increasing the central intensities and perturbing the wings of the line.

Even with the best gratings, these effects cannot be neglected in a single-pass instrument. By chance, a very efficient way of suppressing the ghosts and satellites due to the grating does exist. It is to use the grating in a double-pass arrangement, with an intermediate slit between the first and the second passes on the grating. It is easy to demonstrate that, in such conditions, any ghost or satellite present in the plane of the intermediate slit cannot be transmitted by the second pass on the grating: to bring such a satellite on the intermediate slit, the grating must be turned in such a way that its angle of incidence will no longer correspond to the transmission of the desired wavelength. The additional advantage of the increased resolution obtained in double-passing a grating is, in our opinion, less important than the improvement of the apparatus function given by the use of a narrow intermediate slit.

Figure 1 illustrates this effect. Curves *a* to *d* have been obtained in recording the $\lambda 4880$ line of a stabilized A^+ laser, double-passing a good quality grating† with an intermediate slit progressively enlarged (the entrance and exit slits were set at 80 μm and the four curves correspond to the setting of the intermediate slit at 10, 2, 0·75 and 0·1 mm respectively). The much better quality of the apparatus function in *d* appears clearly.

In practice, even for relatively large photospheric lines, observations made with such a 'pure' instrumental profile give residual intensities slightly smaller than those obtained with the same instrument used with a large intermediate slit.

Another virtue of double-passing the grating is the possibility of rendering negligible the effect of the light scattered and diffused in the spectrometer, by simply recording the position of the 'zero' line in placing the shutter in front of the intermediate slit. In these

† These records have been taken with the large spectrometer of the McMath Hulbert solar telescope (Kitt Peak National Observatory, U.S.A.). The grating was an original ruled by H. D. Babcock (600 lines/mm, ruled surface 150 × 254 mm). We are greatly indebted to A. K. Pierce, who gave us the opportunity to work with that very fine instrument.

conditions, the first pass illuminates always the optics and the inside of the instrument, and the diffused light reaches the detector even when the 'zero' is recorded. Its effect is thus eliminated.

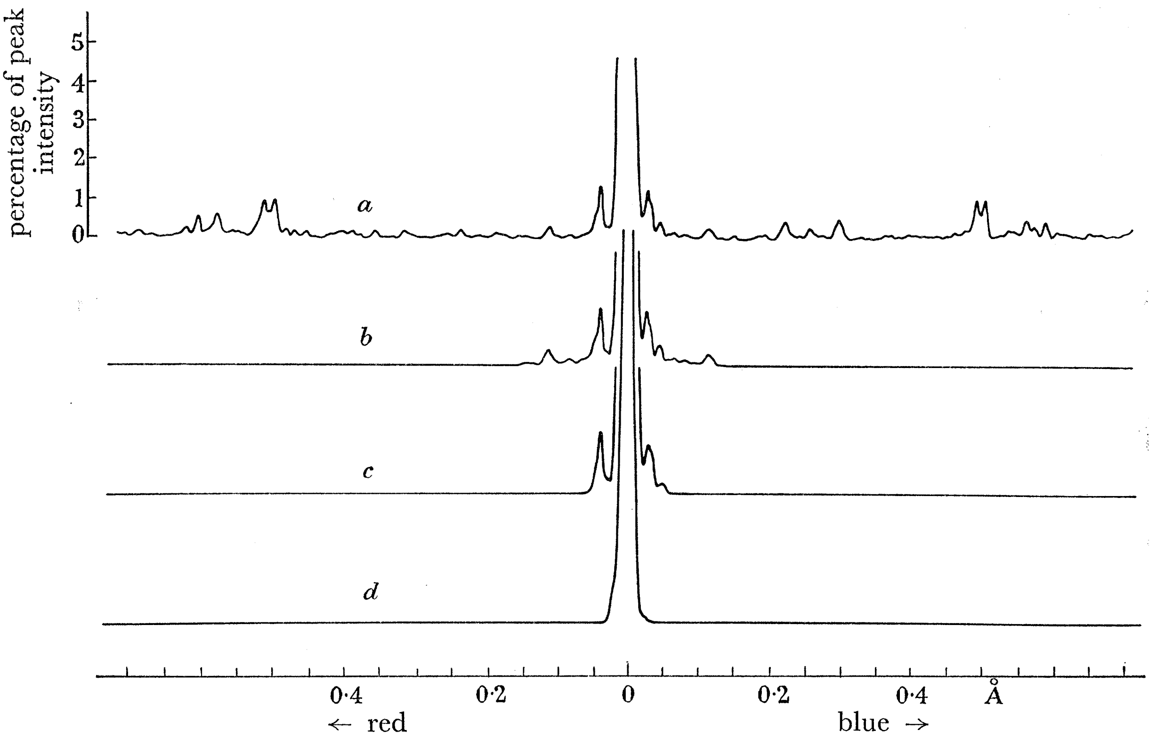

FIGURE 1. Effect of the intermediate slit width on the apparatus function profile.

(b) *Correction for the effect of the instrumental profile*

The physical problem to be solved is well known. Even after elimination of the scattered light, we never observe directly the true shape of a photospheric absorption line, but the result of the convolution of the true profile by the apparatus function of the spectrometer used. In the practical case that we consider here, it is theoretically possible to realize the reverse operation, making the necessary deconvolution to reach the true spectrum. This is based on the fact that, owing to their origin, solar lines are necessarily broad, with, in the sense of their Fourier transforms, a frequency spectrum limited at relatively low values. So, the convolution with a narrow enough instrumental profile, considered as a filtering process, does not erase completely any useful information, but merely changes the relative transmission factor for each individual frequency present in the tracing. However, the correction can only be made if the instrumental profile of the spectrometer is known accurately and if the recorded spectrum is totally free of noise. A complete discussion of these problems will be given elsewhere, so we shall give here only a condensed version of our point of view.

Let us suppose first that we can have the necessary accurate knowledge of the instrumental profile of our spectrometer.†

† We have seen that a direct record of a highly monochromatic line produced by a stabilized laser is an answer to this problem. Other methods can perhaps also be of interest: we are now investigating the possibility of using a spherical Fabry–Pérot filter in front of the spectrometer and of deriving the apparatus function from the observed regularly spaced transmission peaks produced by this filter.

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Most papers published on the question of deconvolution of an experimental curve to correct for the effect of the instrumental function are of a very limited practical use, because they postulate that this function can be simply described mathematically or is, at least, symmetrical. An iterative method must, however, be mentioned because of its great interest: it is the method described in 1933 by Burger & Van Cittert (1932, 1933). Rollett & Higgs (1961) have shown that, in the limit of an infinite number of iterations, that method is exactly equivalent to the complete mathematical treatment using Fourier transforms.

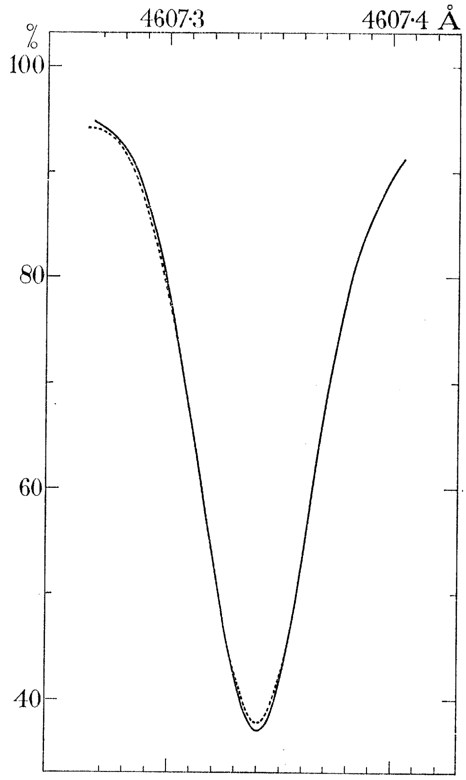

Figure 2. Observed (···) and corrected (—) profiles of the resonance line.

We have worked in a slightly different direction. It is often useful to have the possibility of making the correction in real time, simultaneously with the scanning of the spectrum, with the help of a digital computer associated with the spectrometer. We have investigated the practical possibilities offered by the convolution with the observed spectrum, of a 'corrective operator'. This way of making the correction works very well, leading to the same result as the above-mentioned methods, and is subject to exactly the same limitations. The most important of these limitations is due to the fact that, unavoidably, any correction method produces an increase of the noise level in the record. In practice, a compromise must always be chosen between the importance of the correction and the accepted noise level, but, in any case, the better the records, the more complete can be the correction.

Starting from the high-quality spectra which can now be obtained (see below), one can be confident that, through proper application of these corrective processes, a nearly perfect knowledge of solar line profiles and intensities can be reached.

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As an example of such deconvolution, we show, on figure 2, the observed and corrected profiles of the resonance line.† We must point out that, despite the fact that the halfwidth of the apparatus function of the spectrometer was about one-twelfth the halfwidth of the observed line (4·8 against 62 mÅ), the correction is not negligible (0·8 % on the residual intensity).

3. Amelioration of the signal/noise ratio

The production of tracings with the lowest possible noise is evidently the aim of any solar spectroscopist. We have seen, as described above, that correction techniques can best be applied when the noise is minimum.

On the other hand, it is obvious that the detection and the measurement of very faint absorption lines can only be achieved on very high quality spectra. Such very faint features are of great interest (forbidden lines or lines of the less abundant heavy elements), and a relatively large fraction of the observational work on the solar spectrum will probably be devoted, in the years to come, to their systematic detection.

We shall not present a complete discussion of the various sources of noise in solar tracings (here, again, it will be the subject of a more specific paper), but we must point out the two factors which have to be taken into consideration when one tries to improve the quality of the observations.

First of all, a careful ratio-recording system must be used, and the problems involved are not easy to solve. The measurement of the energy entering into the spectrometer must be done in a relatively narrow wavelength band around the observed spectral region and must also be integrated along the slit to represent as accurately as possible the real distribution of energy on the grating. This reference signal must also be amplified by an electronic system having exactly the same time constant as the one used for the signal collected at the exit slit of the spectrometer. Under these conditions, the ratio between this signal emerging from the exit slit and the reference signal gives a result well compensated for the fluctuations of the atmospheric transparency.

Different practical systems are possible: at the Jungfraujoch, a small plane-parallel piece of fused quartz is placed at 45° after the entrance slit of the spectrometer and reflects a few per cent of the pre-dispersed energy entering the instrument onto the cathode of the reference photomultiplier. To display the spectrum on a chart recorder, for monitoring purposes only, we use a simple analogue method of taking the ratio of the main and reference signals. The final result, considered as representing the best solar spectrum, is in fact processed by an on-line electronic computer, making a digital ratio of the two signals sampled simultaneously. Numerical filtering of the data is also done by the computer, insuring that both signals have had their frequency spectra sharply cut at the same value.

Despite all these precautions, a complete compensation is nearly impossible to reach, mainly because the efficiency of the grating is not the same at all points on its surface,

† The observations and corrections of this line profile have been made in collaboration with Dr L. Neven. We are happy to thank him here for his continuous help in operating the Jungfraujoch laboratory, and for many fruitful discussions about problems of common interest.

giving different weights to the elementary signals coming from various points of the objective. A simple integration along the entrance slit is, under these conditions, not the completely correct answer to the problem. Ideally, it is after one diffraction on the grating that the total energy received in the studied region will have to be measured, but this is technically difficult to do in a scanning spectrometer in which the grating is turning.

The second point of great importance is the frequency spectrum of the atmospheric noise. Until very recently, solar spectroscopists were considering atmospheric noise as 'white noise'. In that case, only the total time spent to record a given wavelength region is to be taken into consideration. An equivalent result is then obtained, if one scans the region slowly, with an equipment having a large time constant, or if one takes, during the same total time, many rapid scans and considers as the result the mean of all the obtained tracings. In fact, it appears that the atmospheric noise is not 'white', but contains a strong $1/f$ component. In other words, atmospheric noise has an excess of low-frequency components and it is easy to see that, under these circumstances, for a given total time of observation, there will be an advantage if one obtains as many rapid scans as possible and takes their mean value as the final tracing. Very roughly, in the visible and the near infrared, an improvement in the signal/noise ratio of about 15 can be obtained if, instead of devoting 1 s to each spectral element in a slow scanning process, we scan 100 times at 0·01 s per element, and take the mean of all these observations.

Rapid scanning requires practically the installation of a real-time averaging system close to the spectrometer. In our opinion, the best method is to make use of an on-line digital computer, because such a computer can perform many more operations than just adding scans. The use of a remote computer, requiring a very large temporary storage, on paper or magnetic tapes, does not appear to be very convenient.

Our laboratory at the Jungfraujoch has been equipped, for this purpose, with a Honeywell DDP 224 computer that we can not only use on-line for data acquisition and reduction, numerical filtering and deconvolution, but that can also serve as a general-purpose computer, when the solar installation is not in use.

The spectrometer itself has been modified to facilitate the rapid scanning of the spectra. Originally, the grating was rotated (Delbouille & Roland 1963) around a vertical axis, by means of a high-precision screw pulling a steel tape rolled onto the 50 cm diameter cylindrical surface of the grating turntable. We have now added, between the screw and the steel tape, a moving-coil mechanism able to pull and release the tape much more rapidly. A small cube-corners two-beam interferometer, illuminated by a He–Ne laser, gives monochromatic fringes which are used, not only to trigger the sampling of the data, but also to servo-control the speed of the moving coil. A simple, lever-type, reductor is used, so that we have about 30 000 equidistant sampling fringes for a displacement of the steel tape of 1 mm (corresponding to a rotation of the grating of 6 minutes of arc or to the scanning of about 10 Å at 5500 Å). That density of sampling points is high enough to allow us to apply efficient numerical filtering techniques. After this process, a much smaller number of points is kept (about one point per mÅ, as mean value) and transfered to magnetic tape. The actual system allows us to scan, in the visible, one angström in a few seconds and to repeat this scanning process, under the control of the computer, to obtain the desired signal/noise ratio.

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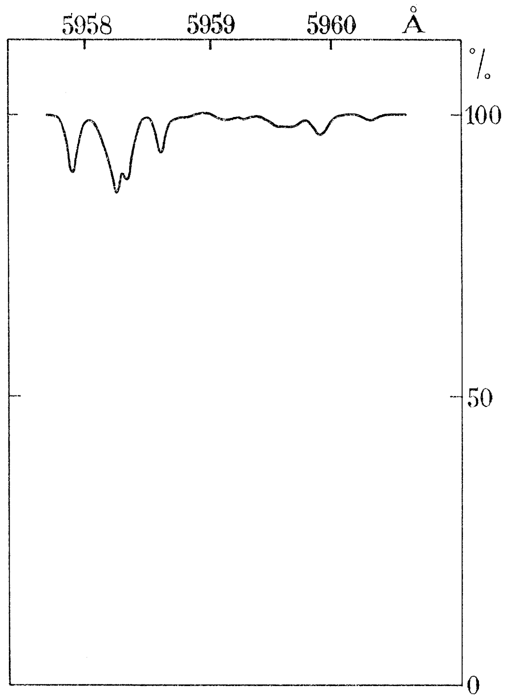

FIGURE 3. The solar spectrum around 5959 Å. Total observation time 30 min.

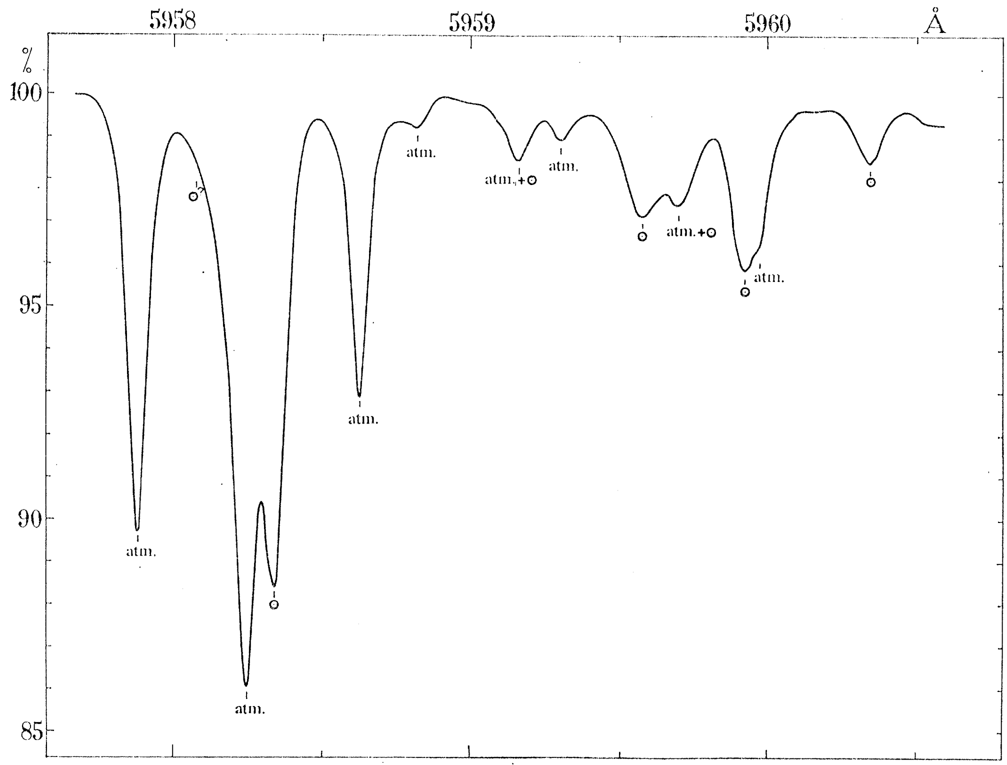

FIGURE 4. Same region as figure 3, with an expanded ordinates scale.

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A few examples of the quality of the tracings obtained in these conditions are reproduced on figures 3 to 9.

The first one refers to the visible region. Around 5959 Å, the noise in the Utrecht Atlas (Minnaert, Mulders & Houtgast 1940) is of the order of 2 %. Figure 3 shows the same

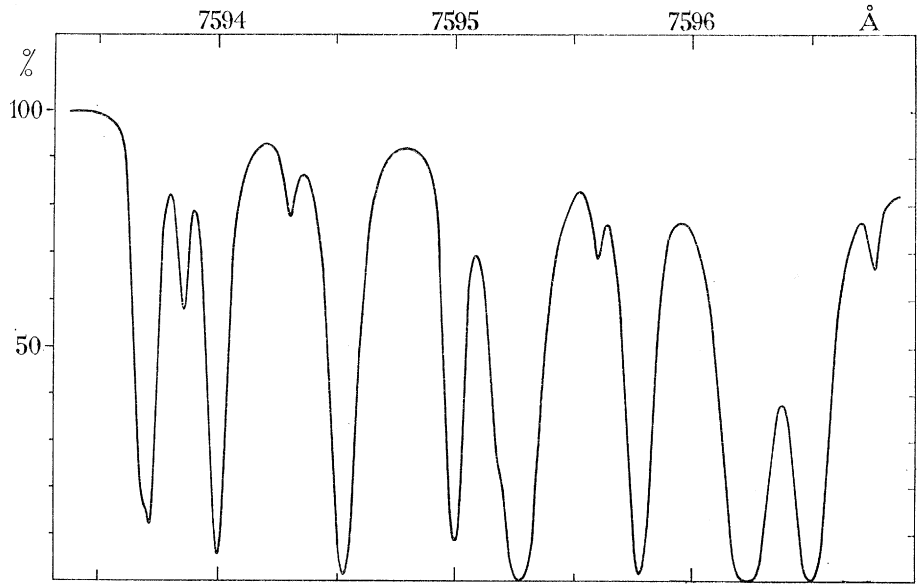

FIGURE 5. Part of the telluric O_2 band near 7595 Å.

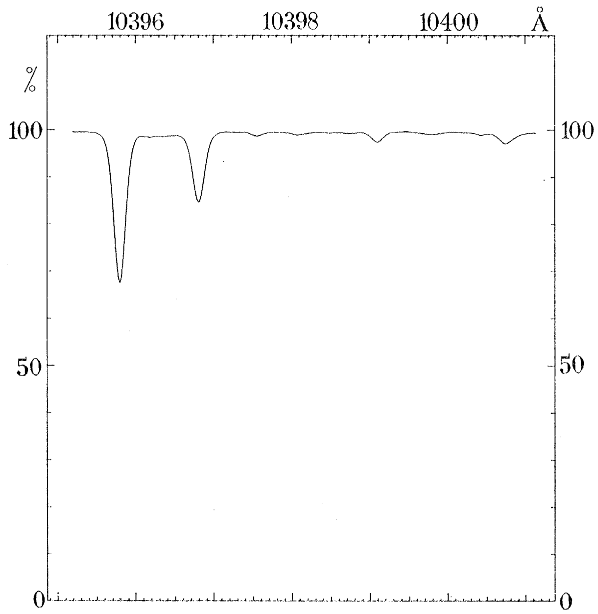

FIGURE 6. The solar spectrum between 10395 and 10401 Å. Total observation time 80 min.

region, recorded at the Jungfraujoch, using the above-mentioned techniques. Figure 4 corresponds to an expansion of the ordinate scale, showing more clearly faint absorption features. The signal/noise ratio appears of the order of 1000.

Figure 5 gives the head of the atmospheric oxygen band at 7593 Å. The first line appears as just resolved. A comparison of that result with the corresponding region in

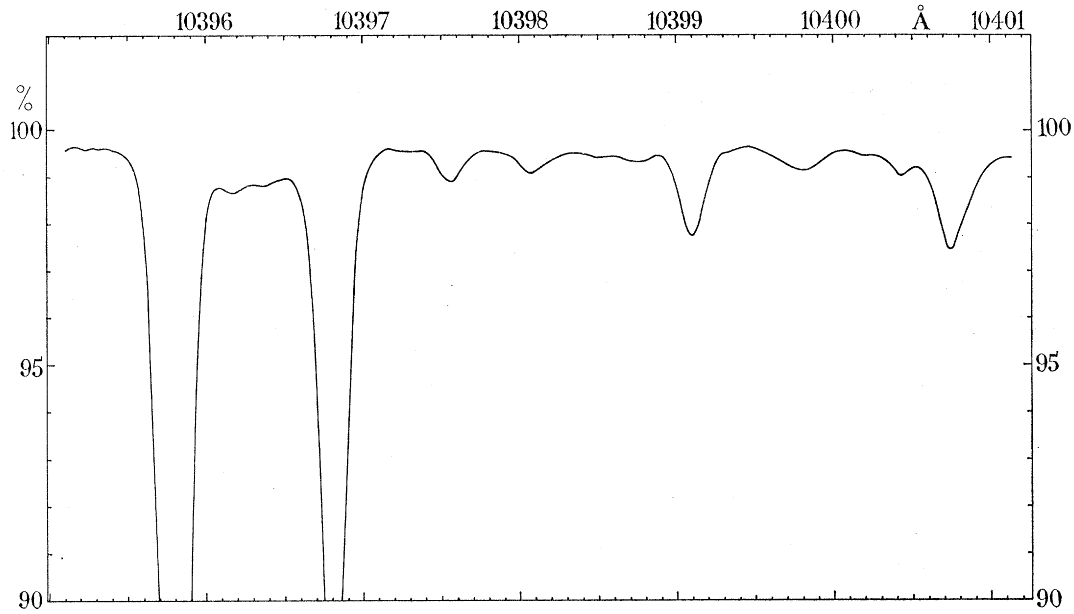

FIGURE 7. Expanded ordinates scale of the region λ 10396 to λ 10401.

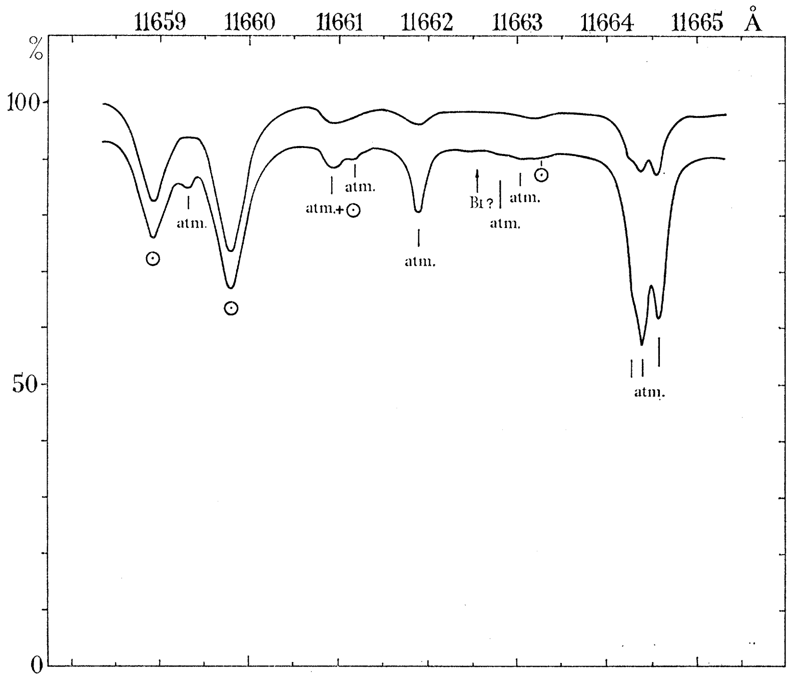

FIGURE 8. λ 11658 to λ 11665 region. The upper tracing has been recorded on a relatively dry day. The lower one shows more intense telluric water absorption lines. Each record has been obtained in 90 min.

our atlas published in 1963, using the same grating in a single-pass arrangement, demonstrates the increase in resolution obtained during these last years. To be noticed also is the absence of diffused light: the more intense lines are reaching the zero of the intensity scale.

Figure 6 shows the region 10395 to 10401 Å (this record has been taken to see if the presence of the two [N I] at 10397·74 and 10398·16 Å was detectable (Lambert & Swings

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1967). Here again, a reproduction of the same spectral region with an expanded intensity scale (figure 7) shows the low remaining noise content (in the same region, our 1963 atlas has a signal/noise ratio of only 100).

The last example, figures 8 and 9, corresponds to the region around 11 660 Å. It has been taken to determine an upper limit of the abundance of boron in the Sun, based on the fact that the two boron lines at 11 660·05 and 11 662·47 Å are undetectable. The two tracings of figure 8 have been taken different days, with a different water content in the atmosphere above the Jungfraujoch. The 'enlarged scale' figure 9 corresponds to the lower curve of figure 8. Lines of atmospheric and solar origins are easily distinguished.

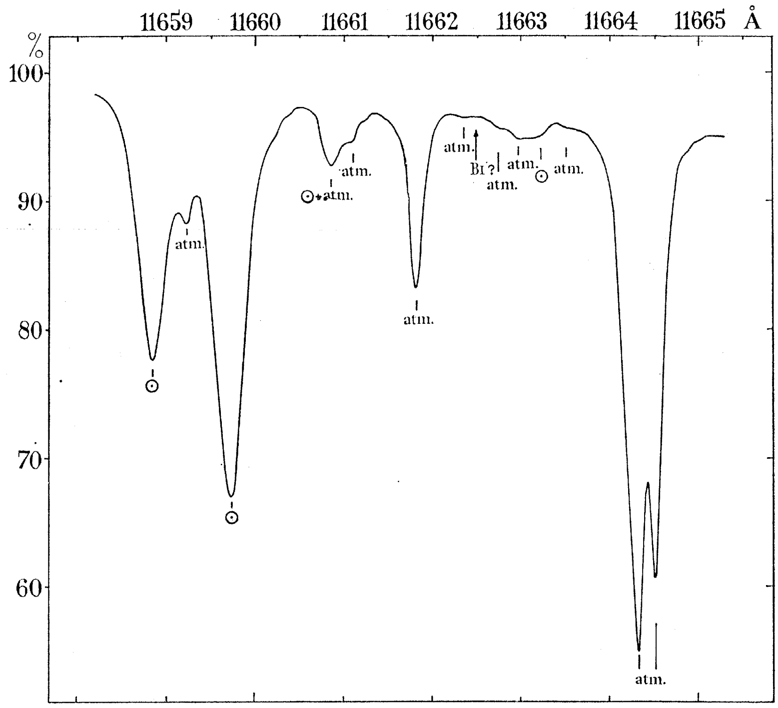

FIGURE 9. Expansion of the intensity scale of the lower curve of figure 8.

4. Liège balloon-borne experiment

Even from a high-altitude station like the Jungfraujoch, large regions of the near infrared solar spectrum are inaccessible. In view to fill these gaps in the knowledge of the solar spectrum, the Institut d'Astrophysique of the University of Liège started two years ago to design and build a gondola that will carry high-resolution spectroscopic equipment to an altitude of 80 000 ft. and make automatic observations of the solar spectrum in the lead-sulphide region.

Figure 10 gives a schematic diagram of the optical system. The guiding on the Sun is made in two steps: first, under control of small commercial solar sensors, the gondola will be rotated, against a flywheel, to allow the plane mirror M_1 to receive solar radiation; the second step is obtained by rotating M_1 around two perpendicular axes, fine solar sensors fixed under M_3 providing an accuracy of a few minutes of arc. Later on, when investigations of centre-to-limb variations of line profiles will be started, a third stage, guiding on the edges of the solar image, will be added.

The 40 cm aperture telescope M_2+M_3, of the Ritchey-Chrétien type, gives an image of the Sun of 6 cm diameter in the plane S. A preliminary monochromator, on the table M, will avoid the overlapping of the different orders of the grating.

The spectrometer itself, of the Ebert–Fastie type, is in principle a 2·5 m focal length reduction of the Jungfraujoch instrument, making use, as much as possible of the experi-

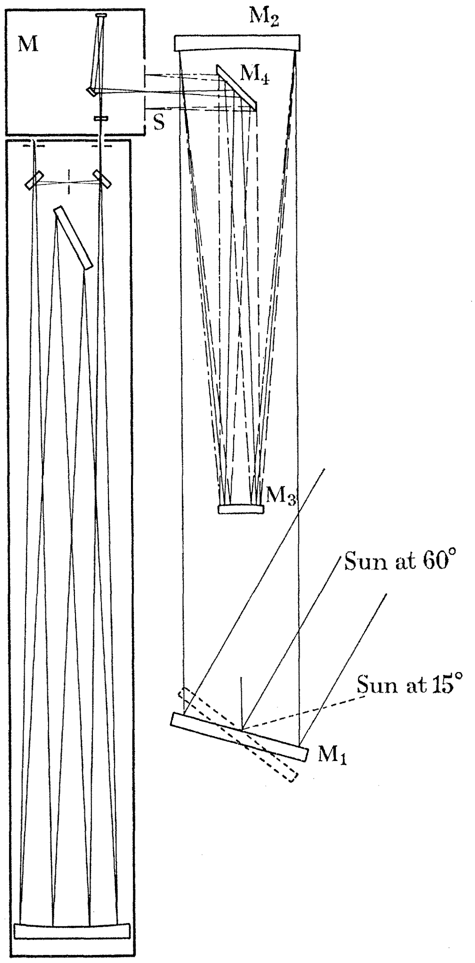

Figure 10. Schematic diagram of the optical system of the Liège balloon experiment.

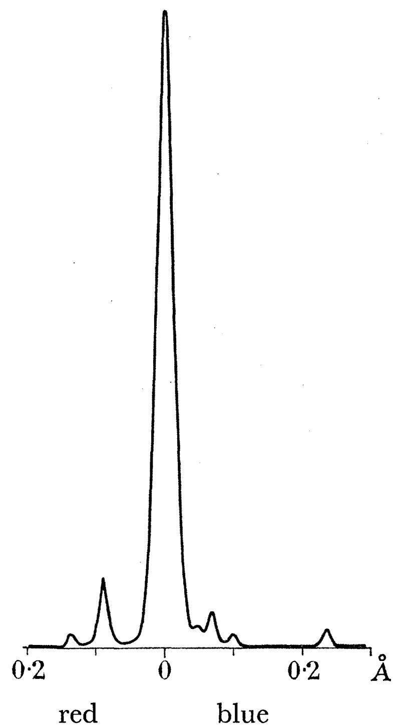

Figure 11. Hyperfine structure of the green natural Hg line as recorded with the balloon spectrometer.

ence accumulated there. The grating is a Bausch and Lomb 'echelle' type (73·25 lines/mm—ruled surface 128 × 201 mm). A double-pass system is used, with a narrow intermediate slit, and the zero is taken by closing that slit. The detector will be a liquid-nitrogen-cooled lead sulphide cell (a liquid-nitrogen transfer system ensuring a minimum of 8 h operation at 80000 ft.).

The scientific results will be digitally recorded, on board, on a computer compatible magnetic tape. Simultaneously, a real-time f.m. link will transmit the recorded spectrum to the Earth, with a lower accuracy, making possible the use of ground commands to

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adjust such critical factors as gain of the amplifiers, speed of rotation of the grating, time constant of the electronic system, etc.

The gondola itself, as well as the frames of the telescope and of the spectrometer, are in aluminium honeycomb, a material giving a maximum stiffness-to-weight ratio. All the mirrors are in aluminium.

Preliminary tests of the spectrometer, in the laboratory, have shown its very high resolving power. Figure 11 is a reproduction of a record of the hyperfine structure of the natural mercury green line; the resolution obtained seems better than 600000.

The first flights are now scheduled for spring 1969, with the collaboration of the National Center for Atmospheric Research (Boulder, Colorado, U.S.A) who will give us all the necessary support to launch, to follow and to recover the gondola. They will be devoted to a survey, at high resolution, of the regions of the solar spectrum inaccessible from the Jungfraujoch. Later on, other flights will probably be made with more specific problems in mind (centre-to-limb variations of line profiles, maximum quality recording of selected regions of the spectrum).

In addition, the gondola will also be used for other solar spectroscopic experiments: in collaboration with Dr H. A. Gebbie (National Physical Laboratory, Teddington, G.B.) Fourier transform observations of the solar spectrum in the submillimeter region will be made during the first flights.

The work at the Jungfraujoch is supported, in part, by the Cambridge Research Laboratories, OAR, through the European Office of Aerospace Research, U.S.A.F., contract AF 61 (052)-955. The necessary funds to develop the Jungfraujoch laboratory and the balloon project are given by the Belgian Government, the University of Liège, and the 'Fonds National de la Recherche Scientifique'.

We are greatly indebted to these organizations and authorities for their continuous help.

We must also thank the Jungfraujoch International Scientific Station and, in particular, its director, the Professor A. von Muralt, for the hospitality offered to us in that high altitude research station.

References (Delbouille & Roland)

Burger, H. C. & van Cittert, P. H. 1932 *Z. Phys.* **79**, 222.

Burger, H. C. & van Cittert, P. H. 1933 *Z. Phys.* **81**, 428.

Delbouille, L. & Roland, G. 1963 Photometric atlas of the solar spectrum between λ 7498 and λ 12016. *Mém. Soc. Roy. Sci. Liège*, spec. vol. 4.

Lambert, D. L. & Swings, J. P. 1967 *Observatory* **87**, 113.

Migeotte, M., Neven, L. & Swensson, J. 1956 The solar spectrum from 2·8 to 23·7 microns. *Mém. Soc. Roy. Sci. Liège*, spec. vol. 1.

Minnaert, M., Mulders, G. & Houtgast, J. 1940 *Photometric atlas of the solar spectrum from λ3612 to λ8771.* Utrecht: Sterrewacht Sonnenborgh.

Rollett, J. S. & Higgs, L. A. 1961 *Proc. Phys. Soc.* **79**, 87.

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