

II. INFRA-RED SPECTROPHOTOMETRY

SUMMARY OF INFRA-RED OBSERVATIONS ON STARS AND PLANETS

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The observations were made with a stellar spectrometer containing a Cashman PbS cell as receiver constructed in 1946 for the 82-inch telescope. The radiation is interrupted 1080 times per second; the small A.C. signal produced by the cell as a result of the fluctuating resistance and 90 V. D.C. voltage is amplified up to 30 million times, rectified, and recorded on a D.C. milliammeter.



Fig. 2. *Infra-red spectrum of Sirius. 0.9-2.5 μ.*

Fig. 1 shows the equipment attached to the 82-inch telescope. On the table are shown the amplifier and meter, on the floor the crystal-controlled constant frequency unit driving the rotating sector (right), voltage control of same unit (centre), and condenser box (left) which lengthens the period of the recording meter to 6 seconds if desired.

The region covered with the PbS cell is from 0.8 to 2.5 μ . The very heavy water vapour absorption (Langley's X, centred at 2.7 μ) blocks out the region from 2.5 to 3 μ to which the cell is still sensitive. Cells cooled with dry ice are sensitive to 3.5 μ , but so far all observations have been made with a cell at observing temperatures. The water vapour in our atmosphere is extremely disturbing; fortunately, some exceedingly dry nights occur at the McDonald Observatory, sometimes equalling the best of Abbot's observing conditions in several desert mountain stations selected for low humidity, including Mt Montezuma, Chili, at 9000 ft. elevation.

The stellar records obtained so far have resolving power $\lambda/\Delta\lambda=80$. Only for Venus has it been possible to increase the resolving power substantially by the addition of an analysing slit over the cell which reduced the effective receiver width from $\frac{1}{4}$ to 0.08 mm.

(resolving power about 250). It is hoped that with a new grating spectrometer now being designed some of the brightest stars like Betelgeuse may be observed with resolution 500; the records shown here are all with resolution 80 except for Venus.

With the low resolution employed so far the only stars which show stellar absorptions are type-A stars and the banded stars (M, N, R, etc.). Fig. 2 shows Sirius with Brackett 10-14 of Hydrogen as well as P_5 , P_6 , and P_7 (P_β , P_γ , P_δ). Especially interesting is R Leonis, showing heavy absorptions at 1.1 and 1.2μ as well as in the 1.5μ region. R Leonis was of visual magnitude 10.8 when recorded.

The determination of the energy curves from the material illustrated is awaiting the results of absorption studies of air and water vapour now in progress in the laboratory in collaboration with Dr Herzberg. Both low resolution curves are obtained for direct comparison with stellar observations and curves with resolution up to 2000, obtained with an analysing slit over the cell. The stars are always recorded with the spectrometer in slitless form (slit width 2 mm. or $15''$) which ensures freedom from disturbances such as atmospheric dispersion. Seeing fluctuations are minimized by the use of a long period (about 6 seconds) for the recording system.

Fainter stars may be recorded with resolution 9, obtained by a single 25° quartz prism replacing the two heavy flint prisms normally used. This low resolution still records the islands of continuous spectrum between the water absorptions. With this combination comparatively faint sources like reddened B stars of 7^m-8^m , the polar cap of Mars, and the rings of Saturn may be observed.

PLANETARY STUDIES

In the spectrum of Mercury no planetary absorptions are indicated, but the 2.2μ maximum is greatly strengthened owing to planetary heat radiation. Venus is shown in Fig. 3 up to 1.8μ . Several new CO_2 bands are shown, each marked by a dot. The other absorptions are due to H_2O except the one O_2 absorption. This record was compared with laboratory spectra of CO_2 having 1400 m. atmosphere path length, obtained jointly with Dr Herzberg. The bands near 1μ are stronger in Venus than corresponds to 1400 m. atmospheres of CO_2 , but the three bands near 2μ correspond to only about 50 m. atmospheres of CO_2 . This enormous difference is partly due to pressure broadening in the laboratory experiment, as was found by additional runs with lower pressure and partly due to decreased penetration into the Venus atmosphere within strong bands. The true amount of CO_2 must be at least 1 km. atmosphere above the cloud layer on Venus (2 km. atmospheres in the observed path).

The reflection curves of Mars and the Moon show that Mars is bluer in the infra-red than the Moon. Other records have shown it to resemble α Persei, type F5, for the region from H_α to $2\frac{1}{2}\mu$. This peculiar reflection curve, coupled with the red visual colour, is not matched by the red rocks of the Painted Desert as has been assumed in the past; instead it was found to correspond closely to a brownish, fine-grain igneous rock, felsitic rhyolite. Comparisons of this kind and also with lunar formations are continuing.

The Mars polar cap was found to have a sharply diminished reflectivity beyond 1.5μ resembling that produced by fine frost crystals deposited on a piece of dry ice (-78°C). Snow at ordinary temperatures has a characteristic reflection curve. This reflection curve may be compared with that of the transmission of a water cell. Melting snow corresponds to a water cell equivalent of about 2 cm., normal snow kept at 0°C . to about 1 cm., and frost deposited on dry ice to about 1 mm. The difference must be caused by the difference in crystal size; evidently in very cold snow total reflection takes place after only about $\frac{1}{2}$ mm. penetration, on the average. The Mars polar cap corresponds to about 1 mm. water-cell equivalent; the rings of Saturn, which show the same characteristic reflection spectrum, to roughly $\frac{2}{3}$ mm. Both may be assumed to be covered with H_2O frost at very low temperatures. On the other hand, CO_2 snow reflects uniformly (white) up to $2\frac{1}{2}\mu$, except for three minor absorptions near 2μ corresponding to the gas absorptions (ω_0 , ω_1 , ω_2).

The green areas on Mars have approximately the same contrast with the surrounding desert regions at 0.6 , 1.0 and 1.6μ , as was ascertained from drift curves obtained with the spectrometer locked at constant wave-length and with an entrance slit adjusted to the size of the largest available green spot (Syrtis Major). The intensity of the green spots was in each case between 0.5 and 0.6 of the surrounding desert region. The conclusion is that these green areas are very different from terrestrial foliage which is dark at 0.6μ , very bright at 1.0μ , and nearly black at 1.6μ . The only terrestrial growth having a similar reflection is that of lichens and certain dry mosses; they fail to show the water-cell type of reflection near 1.5μ . Fig. 4 shows the 1.6μ region of Mars; the two CO_2 bands indicated were calibrated against telluric absorptions. It is found that the Mars atmosphere contains $10-1=9$ times as much CO_2 as the atmosphere above McDonald, distributed over the average path length through the Mars atmosphere, which for a uniformly illuminated disk is four times the amount in a vertical column. Hence the Mars atmosphere contains about $0.8 \times 2\frac{1}{4} = 1.8$ times as much CO_2 as the Earth's atmosphere per square centimetre of surface, the pressure at McDonald being 800 mb.

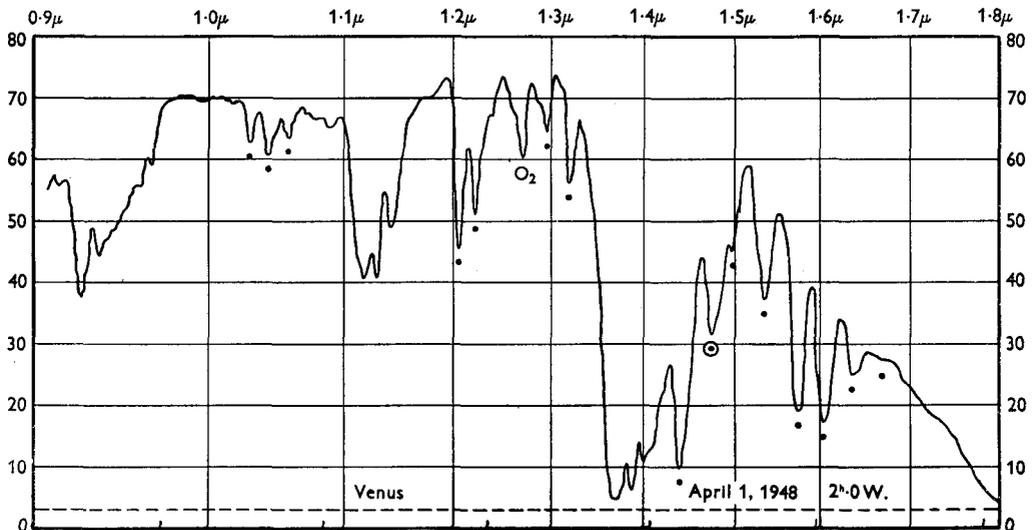


Fig. 3. *Infra-red spectrum of Venus.* • CO_2 bands; © C^{13} isotopic band of 1.435μ (C^{13}), somewhat blended with telluric H_2O . Unmarked: telluric H_2O .

The correctness of the identification of the 1.6μ bands was recently confirmed when during the Mars opposition in February 1948 the three bands at 2μ were found greatly strengthened over the telluric spectrum.

Sensitive spectroscopic tests near 0.3μ failed to reveal the presence of SO_2 or O_3 on Mars. The upper limit on SO_2 is about 0.03 mm. at atmospheric pressure.

Jupiter and Saturn reflect practically no radiation from 1.6 to 2.5μ , as was confirmed with the low dispersion quartz optics. The quantitative interpretation in terms of CH_4 and NH_3 absorption is in progress, using for comparison low dispersion laboratory curves taken jointly with Dr Herzberg. The maximum path length which may be obtained in the laboratory is over 5 km. obtained by multiple reflections; the maximum pressure 10 atmospheres.

Reference has been made to frost on the rings of Saturn. This conclusion was based on the steep drop in reflectivity near 1.5μ . It is entirely consistent with the unusually high albedo of the Ring. From the fact that the outer ring did not form a satellite, an upper limit to the mean density of the ring's particles may be found; it is near unity. Further, the diameters of the inner five satellites of Saturn were measured or estimated.

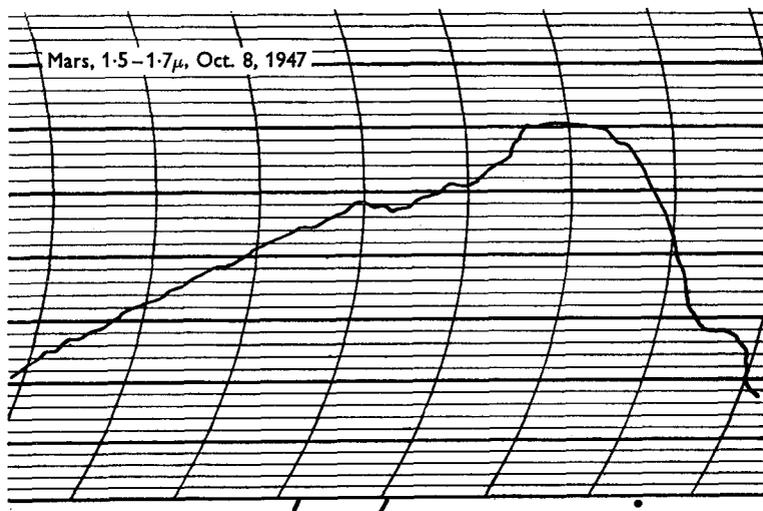
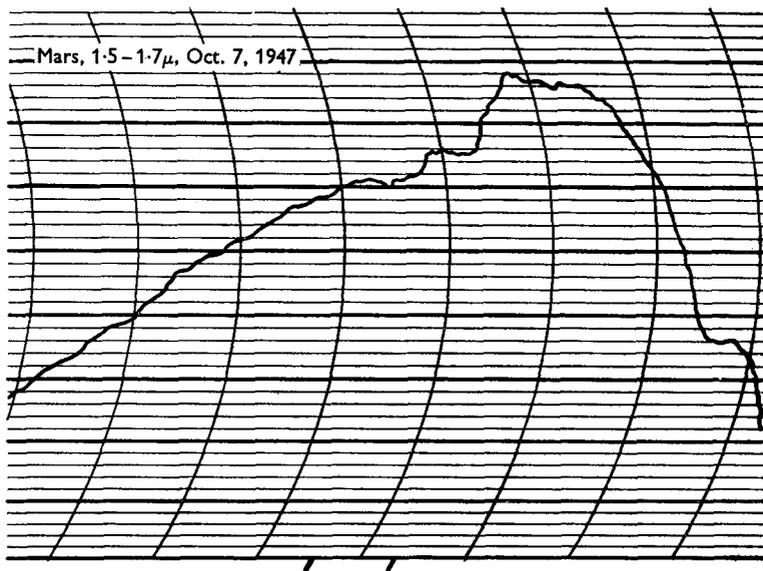


Fig. 4. *Infra-red spectrum of Mars.* CO₂ bands at 1.575 and 1.605 μ ; • H₂O at 1.471 μ .
Left extreme: 1.8 μ .

It was found that these diameters lead to albedos of about 0.8 and densities near unity, except for Dione, for which the density comes out somewhat greater (its mass value may be in error). Pending the derivation of more accurate masses and magnitudes it may provisionally be concluded that the five inner satellites as well as the Rings of Saturn are composed of ice. The rate of evaporation is found to be so small that this constitutes no objection to the conclusion unless the Ring particles are exceedingly small. The high emissivity of frost in the infra-red and the high albedo in the visual cause the equilibrium temperature to be much below the black-body temperature (about 70° K. instead of 100° K.).

INFRA-RED SOLAR SPECTROSCOPY WITH A LEAD-SULFIDE CELL

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The McGregor Tower telescope and spectrometer of the McMath-Hulbert Observatory have been employed in conjunction with a Cashman PbS cell to secure a direct-intensity map of the solar spectrum in the region of 0.8μ to 2.5μ , with a resolution of about 50,000. The spectrometer is of the Pfund type, consisting of a 15,000-line plane reflection grating together with two parabolic and two plane mirrors, the equivalent focal length being approximately $23\frac{1}{2}$ feet. The solar image was produced by a $10\frac{1}{2}$ -inch Cassegrain reflector, which has recently been replaced by a 12-inch by 50-foot off-axis parabola. Spectrometer accessories include a low-dispersion monochromator, designed to eliminate interference from overlapping grating orders, and a light chopper that interrupts the sunlight 1080 times a second. An amplifier designed and constructed by Mr Wallace Wilson of the Northwestern Technological Institute is employed together with a Leeds and Northrup Speedomax pen-and-ink recorder.

The solar map is recorded on very nearly a direct-intensity scale with a dispersion on the recording paper of about 5 mm./Å. The solar spectrum in the regions 1.3 – 1.5μ and 1.75 – 1.95μ is heavily obscured, due chiefly to absorption by H₂O in the earth's atmosphere. The intervening regions, however, are relatively clear and contain a wealth of solar atomic lines, as well as numerous isolated telluric molecular lines and bands.

A systematic programme of identification and measurement, both of solar and telluric lines, is now under way at the McMath-Hulbert Observatory. Progress with the identifications has been slow, largely because of the almost complete absence of high-resolution laboratory studies in the lead-sulfide region of the infra-red spectrum. The wave-length scale has been established by the method of overlapping orders, to an accuracy of about 0.1 Å. The measurement of wave-length is now complete in the 'window' between 1.52 and 1.75μ and the measurement of lines in the region 2.1 – 2.4μ is in progress. Approximately three hundred new solar atomic lines have been found in the first window by comparison of tracings made with high and low sun. Nearly one hundred of these lines have been identified on the basis of wave-lengths computed from differences between known atomic energy levels. The elements for which lines have been found include H, C, Na, Mg, Al, Si, Fe, Mn and Ni. No ionized atoms have as yet been identified, although a preliminary search has been made on the basis of published term lists. The vast majority of the identified lines have excitation potentials in excess of 5 V.; analysis of their intensities both at the centre of the solar disk and at the extreme limb should have an important bearing on the solar-atmospheric model.

Among the most interesting features of the infra-red spectrum are the band systems of molecules originating in the Earth's atmosphere. Among these are the four well-known bands of CO₂ in the 1.6μ region, which have been resolved for the first time, and three strong bands of CO₂ at 2.1μ . The solar map reveals also a number of new molecular band systems, the most interesting of which are four bands at 1.66 , 2.30 , 2.32 and 2.37μ , which have been identified as the $2\nu_3$, $\nu_1 + \nu_4$, $\nu_3 + \nu_4$ and $\nu_2 + \nu_3$ transitions of CH₄ in the Earth's atmosphere. A comparison of the $2\nu_3$ telluric line intensities with those produced by a

measured quantity of methane in the laboratory indicates an abundance corresponding to 1.7 atmo-cm. An analysis of the CH₄ spectrum is now in progress and will be published in the *Astrophysical Journal*. Eight telluric lines in the 2 μ region have been tentatively identified as arising from NH₃. Confirmation of the NH₃ identifications must await observations of the fundamental bands in the 10 μ region.

In process of preparation is an atlas of the infra-red solar spectrum, which will consist of reproductions of the direct-intensity tracings throughout the region from 8000 to 25,000 Å. The new atlas will therefore partially overlap with, and extend the valuable map by Minnaert, Houtgast and Mulders in the photographic region.

SUR LA PRÉSENCE DE CH₄, N₂O ET NH₃ DANS L'AMOSPHÈRE TERRESTRE

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Durant ces derniers mois, nous avons eu la possibilité d'enregistrer le spectre infra-rouge du soleil, à grande dispersion, entre 2.8 μ et 5.1 μ ainsi qu'entre 7 μ et 11.7 μ . Ces observations ont été effectuées à l'Université d'Ohio State (Columbus, Ohio, E.U.), en utilisant un spectrographe prisme-réseau, construit par le Dr R. Noble, sous la direction du Prof. H. H. Nielsen.

Les enregistrements obtenus ont conduit, en janvier 1948, à la découverte de méthane dans l'atmosphère terrestre.* Ce gaz a été identifié en repérant, dans le spectre solaire, treize raies de la bande fondamentale de CH₄, située à 3.4 μ . Dans la suite, des raies de la bande fondamentale de CH₄ située à 7.7 μ ont aussi été identifiées dans le spectre solaire.† De plus, en mai 1948, R. McMath, O. Mohler et L. Goldberg‡ ont signalé que quatre bandes de CH₄ apparaissaient dans le spectre solaire entre 1 μ et 2 μ . Notons que les raies observées à 3.4 μ et 7.7 μ sont perturbées par des raies de vapeur d'eau. Elles ne peuvent être utilisées pour une estimation quantitative du CH₄ atmosphérique; mais les raies observées à 1.6 μ conviennent particulièrement bien dans ce but.

Les nouvelles observations du spectre solaire ont aussi permis de confirmer la présence du N₂O atmosphérique, proposée pour la première fois par A. Adel en 1939.§ La structure fine des bandes de N₂O à 3.9 μ , 4.5 μ et 8.6 μ apparaît nettement sur les spectrogrammes obtenus à l'Université d'Ohio State.

Concernant NH₃, signalons que la présence de ce gaz dans l'atmosphère terrestre a été récemment proposée par O. Mohler, L. Goldberg et R. McMath.|| D'après ces auteurs, les nombres d'ondes de huit raies intenses du spectre de NH₃, situées vers 2 μ concordent à ± 0.05 cm.⁻¹ près avec des raies observées dans le spectre solaire. Notons que ces raies sont dans une région où seules des bandes de combinaison de NH₃ ont été signalées. Comparativement à celles-ci, les bandes fondamentales de NH₃ devraient donc être intenses dans le spectre solaire. La bande fondamentale de NH₃ à 10.5 μ est particulièrement bien située pour vérifier la présence du NH₃ atmosphérique, car, dans cette région, il y a relativement peu de raies dans le spectre solaire.

Nous avons comparé de nouveaux spectres de NH₃ pris, en laboratoire, dans la région 10.5 μ , par R. Chapman, à l'Université d'Ohio State, d'une part avec les spectres du soleil obtenus à Flagstaff (Arizona, E.U.) par A. Adel en 1940,¶ d'autre part, avec de nouveaux spectres du soleil enregistrés à Columbus, le 3 et 8 juillet 1948. Nous avons constaté que les raies de NH₃ n'apparaissent pas dans les spectres solaires considérés. De nouvelles observations sont nécessaires pour déterminer s'il existe une concentration locale de NH₃ près de Pontiac (Michigan, E.U.), où les enregistrements de O. Mohler, L. Goldberg et R. McMath ont été obtenus.

* *Phys. Rev.* **73**, 519, 1948; *Ap. J.* **107**, 400, 1948.

† *Phys. Rev.* **74**, 112, 1948.

‡ *Phys. Rev.* **73**, 1203, 1948.

§ *Ap. J.* **90**, 627, 1939; **93**, 509, 1941.

|| *Phys. Rev.* **74**, 352, 1948.

¶ *Ap. J.* **94**, 451, 1941.