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D. G. Murcray, F. H. Murcray, W. J. Williams and T. G. Kyle

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Infrared solar spectrum as observed from balloons

By D. G. Murcray, F. H. Murcray, W. J. Williams and T. G. Kyle
Department of Physics, University of Denver

[Plate 10]

The variation of the infrared solar spectrum in the region from 2·2 to 13 μm with altitude has been observed during a series of balloon flights. The primary objective of these flights has been to obtain data concerning the transmittance of the Earth's atmosphere in this wavelength region particularly at altitudes from 13 to 31 km. The transmittance observed during these flights are compared with the transmittances calculated using a line-by-line integration technique. It is shown that it is possible to get good agreement between the observed and calculated results provided the distribution of the absorbing molecule is known.

In addition to the flights during which only relative data were obtained, two flights were made during which absolute spectral data were obtained. From these data the spectral radiance of the Sun has been determined without the complication of correcting for atmospheric effects. The results are in good agreement with the results of other investigators in the wavelength regions where such measurements have been made from the ground.

1. Introduction

For a number of years our group at the University of Denver has been measuring the variation of the atmospheric spectral transmittance with altitude using balloon-borne instrumentation. Data pertinent to the problem have been obtained by studying the variation of the infrared 'solar' spectrum with altitude. Thus these studies have been concerned with the telluric absorptions superposed on the solar spectrum. The early experiments employed a prism spectrometer and data were obtained in the region from 1 to 15 μm. Recently we have replaced the prism spectrometer with a $1\frac{1}{2}$ m Czerny-Turner grating instrument with a resulting increase in resolution.

While the primary objective of the program has been to obtain experimental data pertinent to the transmittance problem, the over-all objective has been to arrive at a technique for predicting the atmospheric transmittance to within the accuracy achieved in the experimental studies. In the initial studies comparisons were made with the theoretical results presented by other investigators. This has not proved feasible for the later results since the published theoretical results are generally not given for the same resolution, altitude, solar zenith angle, etc., as the experimental. In view of this a technique has been developed for predicting the transmittance to be expected. Using this technique it has been possible to get good agreement between observed and predicted transmittance.

Relative data are adequate for the selective transmittance studies and most flights have been made without performing an absolute calibration of the balloon-borne system. Two flights have been made where the instrumentation was calibrated before and after the flight. These flights were made to measure the solar spectral radiance in the 4–5 μm region and in the region from 2·16 to 2·5 μm.

2. Instrumentation

The balloon-borne instrumentation consists of three major items: the biaxial oriented telescope, the infrared spectrometer and the data-recording system. The telescope employs a plane mirror servo oriented in elevation and a spherical mirror with a radius of curvature of 290 cm and a diameter of 25 cm. The solar radiation is reflected from the plane mirror onto the spherical mirror. The converging beam from the spherical mirror passes through a hole in the centre of the plane mirror and the centre of the bearing column supporting the telescope, about which the telescope is orientated in azimuth. The solar image is formed about 10 cm below the base of the telescope system allowing room to mount the optical experiment to the seeker base plate. The image is 13·5 mm in diameter.

The payload rotation rates during ascent are much greater than those encountered after half an hour or so at floating altitude. To maintain pointing accuracy during ascent both high torque and high peak rotational capacity are required. In order to achieve this each servo assembly is composed of a d.c. motor run at a constant rev./min driving two hysteresis clutches in opposing directions. The outputs are geared down and combined on an output shaft coupled by a chain drive to the respective axis to be rotated. In a balance condition both clutches are partially activated thus opposing each other.

The Sun as observed through the Earth's atmosphere does not offer an ideal source for the sensors of a servomechanism since it is a source of variable intensity and contrast with its background. For a servomechanism to operate at peak performance it is necessary to have some method of maintaining a constant operating level when it is subjected to variations in the source intensity. This necessitates monitoring the source intensity and adjusting the system gain accordingly. To accomplish this the servo error signal is derived from a pair of voltage divider networks, each composed of two cadmium sulphide cells, one monitoring the position of the Sun, the other its intensity. In this way the change in voltage per unit error angle is kept nearly constant over a wide intensity range. The system has successfully pointed at intense lamps, sunrises, and the noon and midnight Sun from an altitude of 31 km.

The eye assemblies, electronic components and clutch systems are carefully selected for matching characteristics to maintain a system linear about the balance point. Tube type d.c. amplifiers are used to minimize drift with time and to maintain characteristics over a wide temperature range.

Two spectrometers have been used. The first is a small prism spectrometer of the Littrow type designed for balloon use. The second is a $\frac{1}{2}$ m Czerny–Turner system used double pass, also designed for balloon use. A prism predisperser is used to separate orders in the grating instrument since it is more versatile, yields better spectral separation and avoids the variation of spectral transmission associated with filters near their cut-on and cut-off wavelengths. Figure 1 shows the optical diagram of the grating instrument. The collimating mirrors of the grating have a radius of curvature of 1 meter and a diameter of 12·7 cm. The grating is a 10·2 cm square 75 line/mm replica grating blazed at 12 μm. The radiation is double passed by replacing the exit slit with a corner reflector. After the second pass the radiation is reflected out from the side of the instrument and focused onto the detector. The radiation is mechanically interrupted between the first and second pass to produce an a.c. signal at the detector. This interruption is accomplished by means of an American Time Products electronically driven tuning fork placed between the two mirrors of the corner reflector at the focus of the first pass. Two chopping frequencies have been used, 30 and 100 c/s.

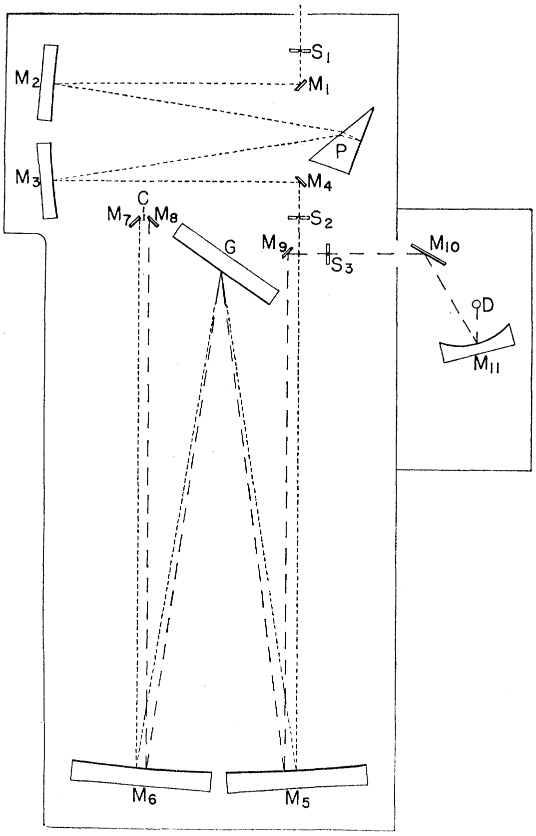

Figure 1. Optical diagram of the Czerny–Turner grating spectrometer and prism predisperser with an outline of the mounting base. The radiation is double passed using a corner reflector at the focal point of the first pass. Radiation is mechanically intercepted with a tuning fork (*c*) between the mirrors of the corner reflector.

Spectral scanning is accomplished by rotating the grating, by means of a level arm attached to the grating mount shaft to follow a specially cut cam. The angular relationship between the grating and the prism in the predisperser has been calculated for the various orders and a cam has been cut containing this information. The prism is coupled to the grating with this cam thus assuring that the correct spectral region is passed through the predisperser at all times. A manual rotation of the cam to preset positions permits the use of the second, third, fourth, fifth, sixth or twenty-fifth order with a calcium fluoride prism or the first and second order with a potassium bromide prism. The grating drive system employs a gear box which allows a number of scan speeds to be selected. For most of the balloon flights the spectral region of interest is scanned in three minutes.

To date flights have been made in which uncooled lead sulphide cells and Schwarz and Reeder thermocouples were used as detectors. The signal from the detector is amplified and synchronously rectified. It is recorded in digital form by means of an on-board digital

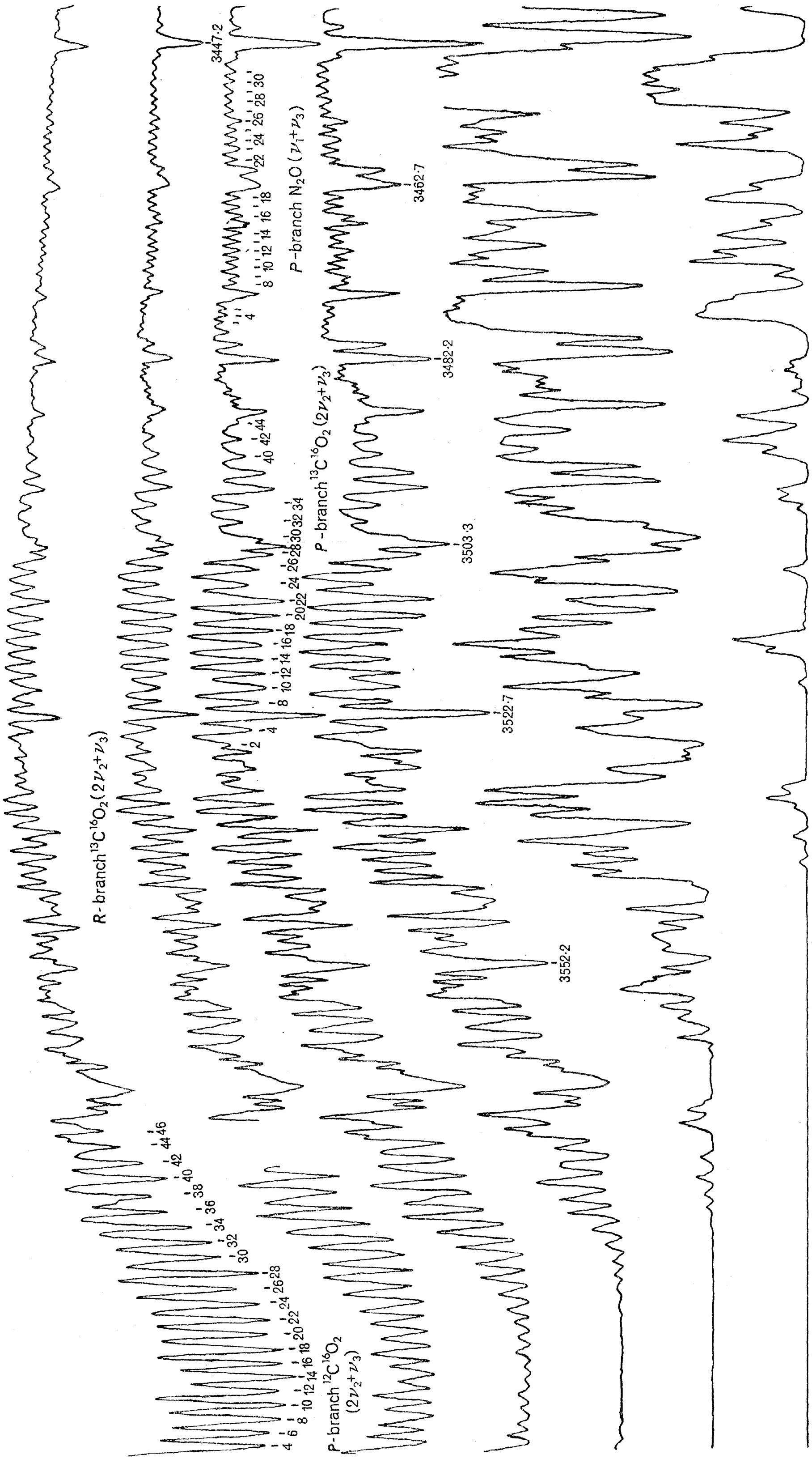

FIGURE 3. Variation of the infrared solar spectrum with altitude. Tracings of the analog telemetry data from the 9 December 1964 balloon flight showing the ^{13}C $^{16}O_2$ band and the N_2O band on the long wavelength side of the 2·7 μm region. (Tracings are displaced in ordinate for clarity and were obtained at altitudes of 16·8, 13·2, 10·5, 8·1, 5·8 and 3·1 km, respectively from top to bottom.)

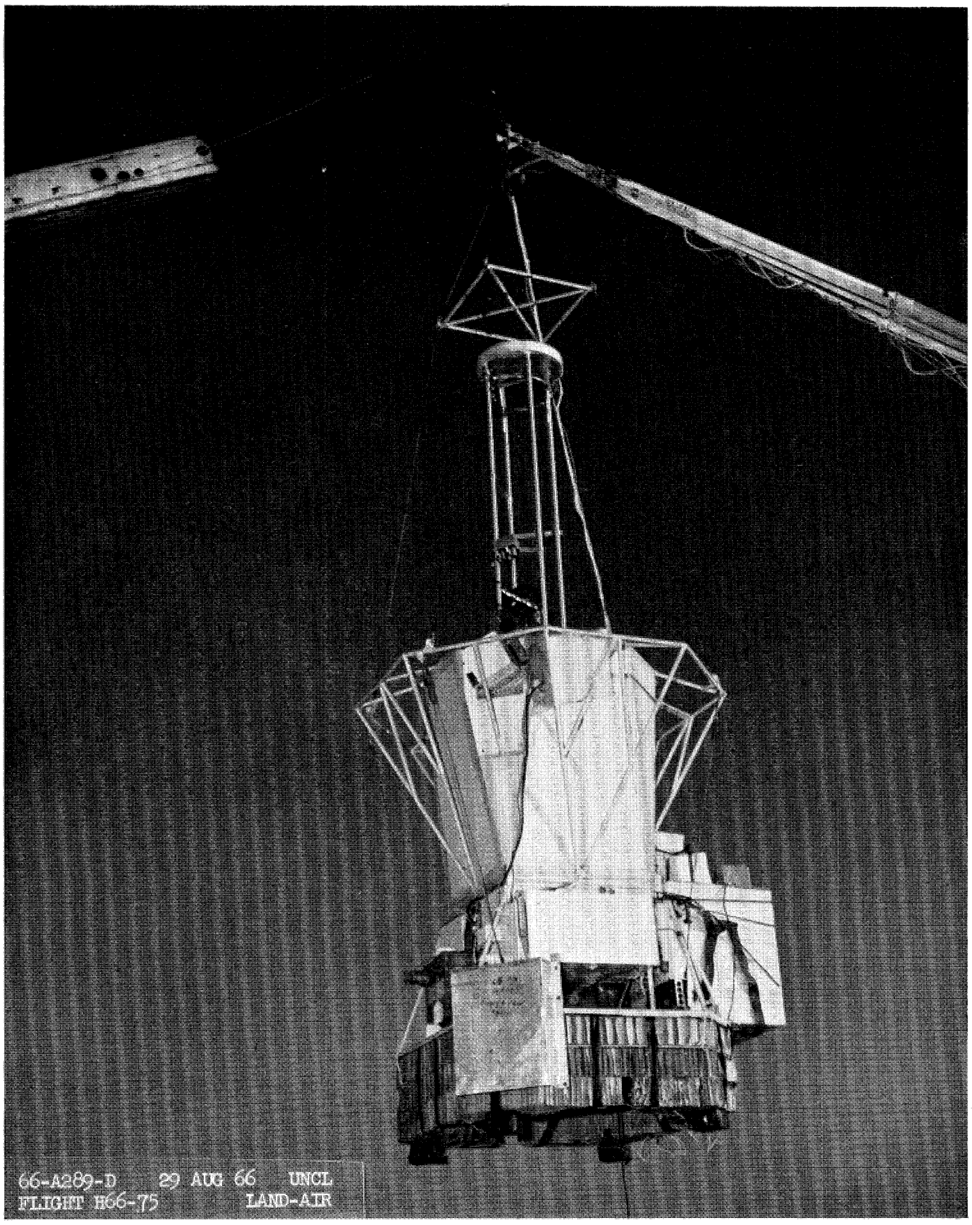

FIGURE 2. Photograph of the balloon payload in flight configuration.

magnetic tape recording system designed and constructed by our group for balloon use. It has a 6 h recording capacity at a sampling rate of 200 samples per second. The recording format is directly compatible with I.B.M. computers which simplifies data handling. The input consists of eight channels each sampled 25 times per second. The data are also telemetered to the ground in analog form using an f.m./f.m. telemetry system. The total balloon-borne system in flight configuration is shown in figure 2, plate 10.

Figure 3 shows samples of the original data obtained during a balloon flight. These spectra have been taken direct from the analog recording of the telemetered data. In order for the data to be compared with the theoretical predictions it is necessary to convert these data from voltage versus time into transmittance versus wave-number. The most time-consuming portion of the data reduction and the one most subject to error is the determination of the so-called vacuum envelope, i.e. the voltage that would have been recorded if the instrument were above the Earth's atmosphere. This is done on the basis of the spectra obtained at floating altitude when the absorptions are least. Once the envelope has been determined the remaining data reduction can be performed by a computer since the data are already available in digital form. Figure 4 shows the change in transmittance with altitude in the $2{\cdot}7\,\mu$m region. This is a portion of the data obtained during a flight made from Chico, California.

In order to compare the observed transmittance with that predicted theoretically it is necessary that the theoretical spectrum be given for the same resolution, altitude and solar zenith angle as the experimental spectrum. A technique has been developed for calculating the atmospheric transmittance using a line-by-line integration technique. The initial analysis was performed for the $4{\cdot}3\,\mu$m CO_2 band. Figure 5 shows a comparison of the theoretical transmittance calculated by this technique with that observed during a balloon flight made from Holloman AFB. This spectrum was obtained at a relatively low altitude (10 km) but is included since it shows the necessity of including a modification to the line shape used in the calculations. The Benedict modification has to be used when the absorption in this region is strong. This modification to the line shape is not as important when the absorption is weak as indicated in figures 6 and 7. These results indicate the agreement that can be obtained in the slant path calculations at least in the case of a molecule which is approximately uniformly distributed in the earth's atmosphere. Figure 8 shows a similar comparison between the theoretical and predicted absorption in the case of water vapour. Here the comparison is made with laboratory data, and the results will be used to determine the distribution of water vapour in the stratosphere since in general this is not known from other data.

It is not necessary to calibrate the spectrometer in order to obtain data pertinent to the problem of selective absorption in the Earth's atmosphere; however, in order to determine the over-all attenuation it is necessary to calibrate the instrument absolutely. Two flights have been made in which the total system has been calibrated against a blackbody source before and after the flight. Since the Sun is a very intense source and it is desirable to calibrate the system as it is flown rather than changing spectrometer slits, it was necessary to have a blackbody reference source that can be used at fairly high temperatures. A conical blackbody cavity constructed out of tungsten foil was used as the source. By running relatively large currents through the system it was possible to achieve temperatures close to 3000 °K over an aperture approximately $\frac{3}{4}$ in. in diameter. This source was imaged on the spectrometer entrance slit through the total optical system and calibration spectra were run while the source was maintained at a number of temperatures in the range from 2200 to 3000 °K. Calibrations of this sort were performed with the prism spectrometer prior to a

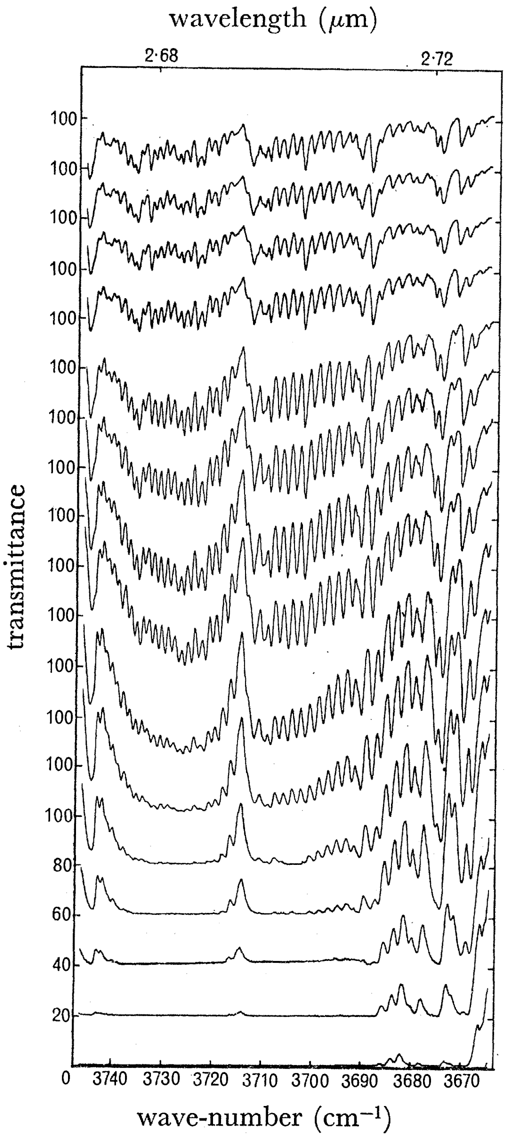

FIGURE 4. Samples of the reduced data obtained during the 30 September 1965 balloon flight at Chico, California, showing the $\nu_1+\nu_3$ CO_2 band at 3716 cm^{-1}. The zero transmittance level of successive records is displaced by 20%. Beginning at the bottom the records were obtained at altitudes of 5·2, 6·1, 7·2, 8·6, 10·2, 11·9, 13·6, 16·9, 18·0, 20·3, 22·2, 27·2, 29·7, 29·7 and 29·7 km, respectively.

flight covering the 4·3 μm region and with the grating spectrometer prior to a flight covering the so-called window between 2·16 and 2·5 μm. The data covering the 4·3 μm region were presented in a previous report (Murcray, Murcray & Williams 1964). Figures 9 to 11 present some of the data obtained during the flight with the grating instrument.

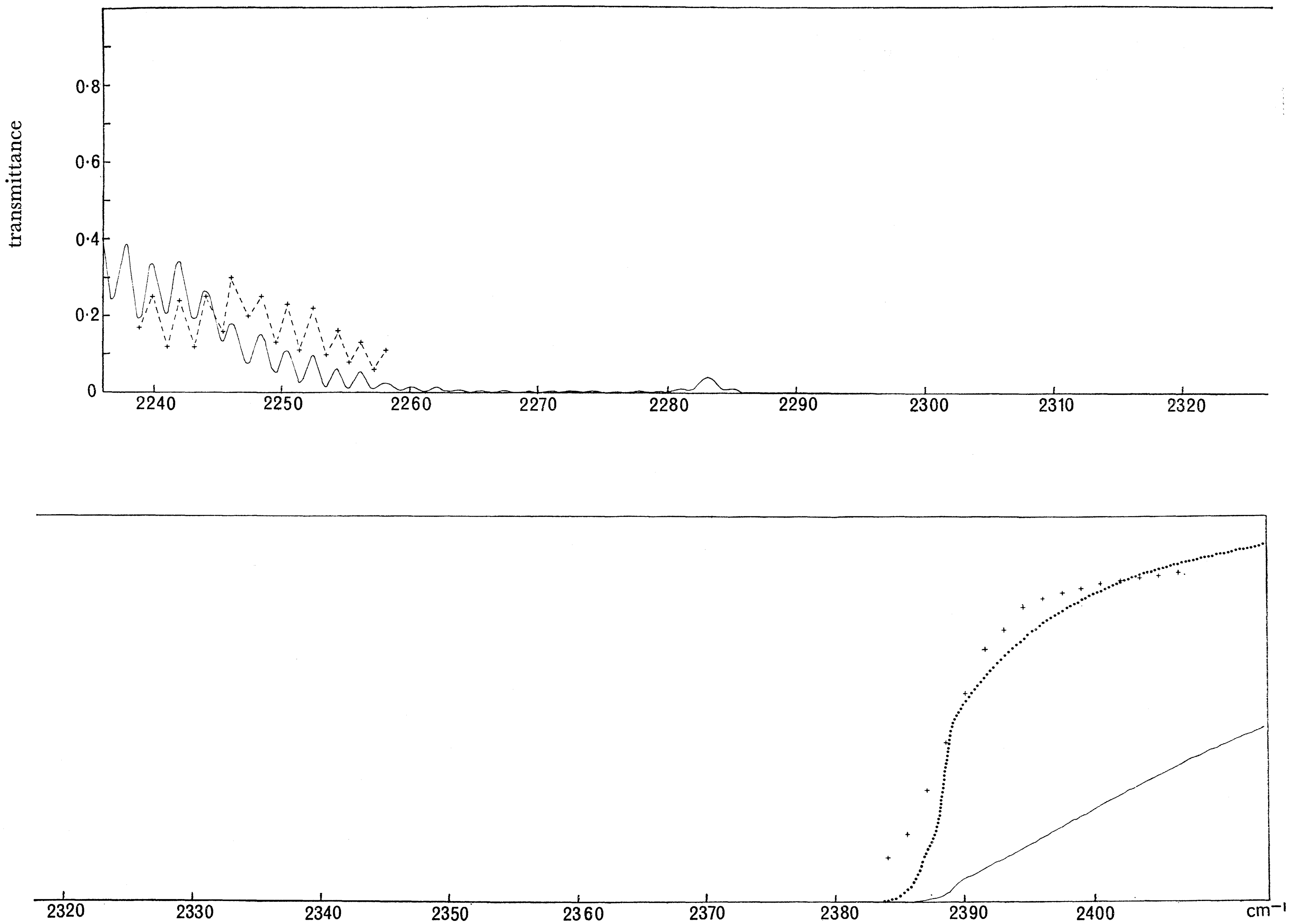

FIGURE 5. Comparison between experimental and theoretical atmospheric spectral transmittance data for the 4·3 μm CO_2 band at an altitude of 10·7 km and a solar elevation of 14·65°. —, Calculated Lorentz line; +, experimental; ···, calculated Benedict line.

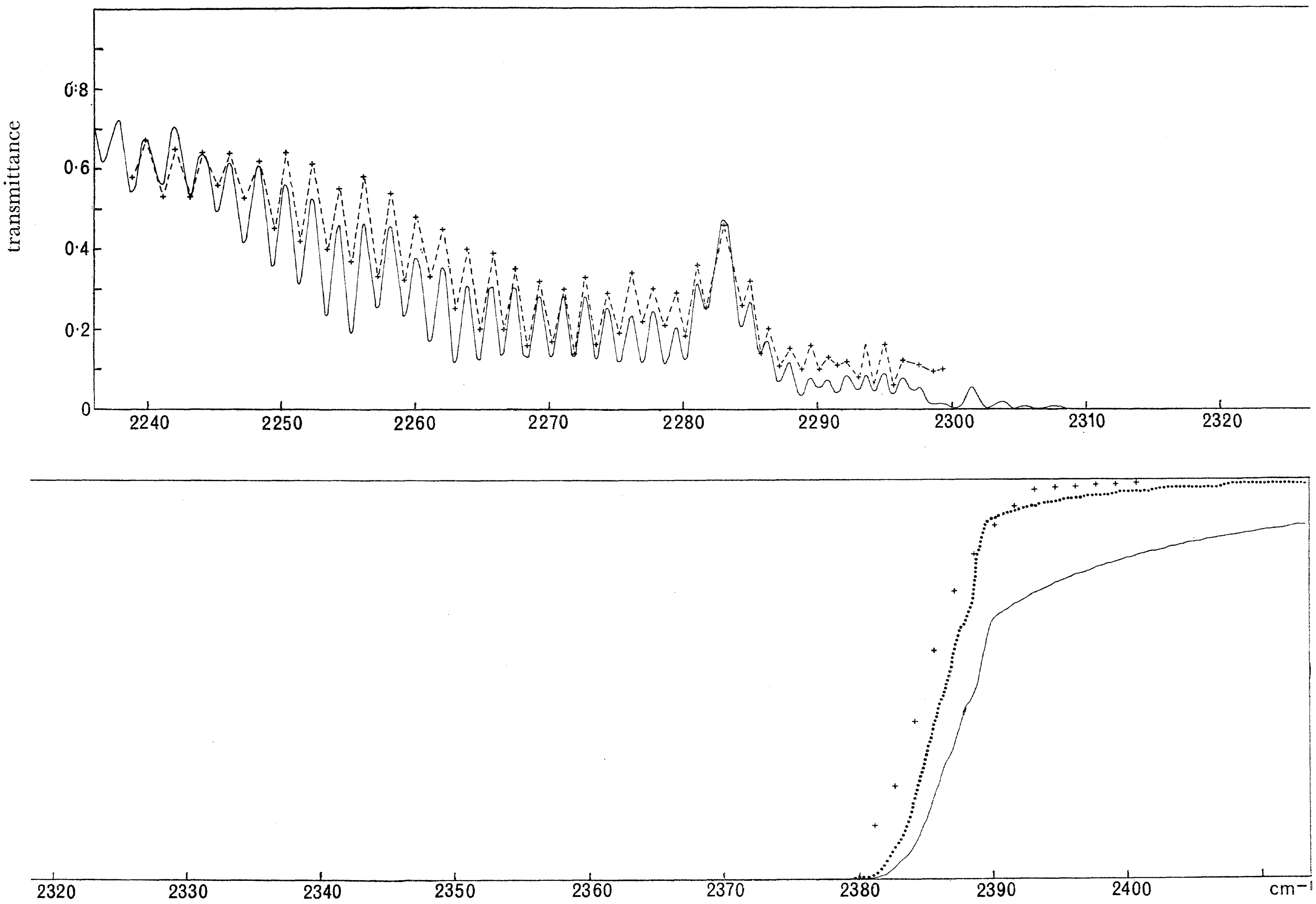

FIGURE 6. Comparison between experimental and theoretical atmospheric spectral transmittance data for the 4·3 μm CO_2 band at an altitude of 15·8 km and a solar elevation of 19·59°. —, Calculated Lorentz line; +, experimental; ···, calculated Benedict line.

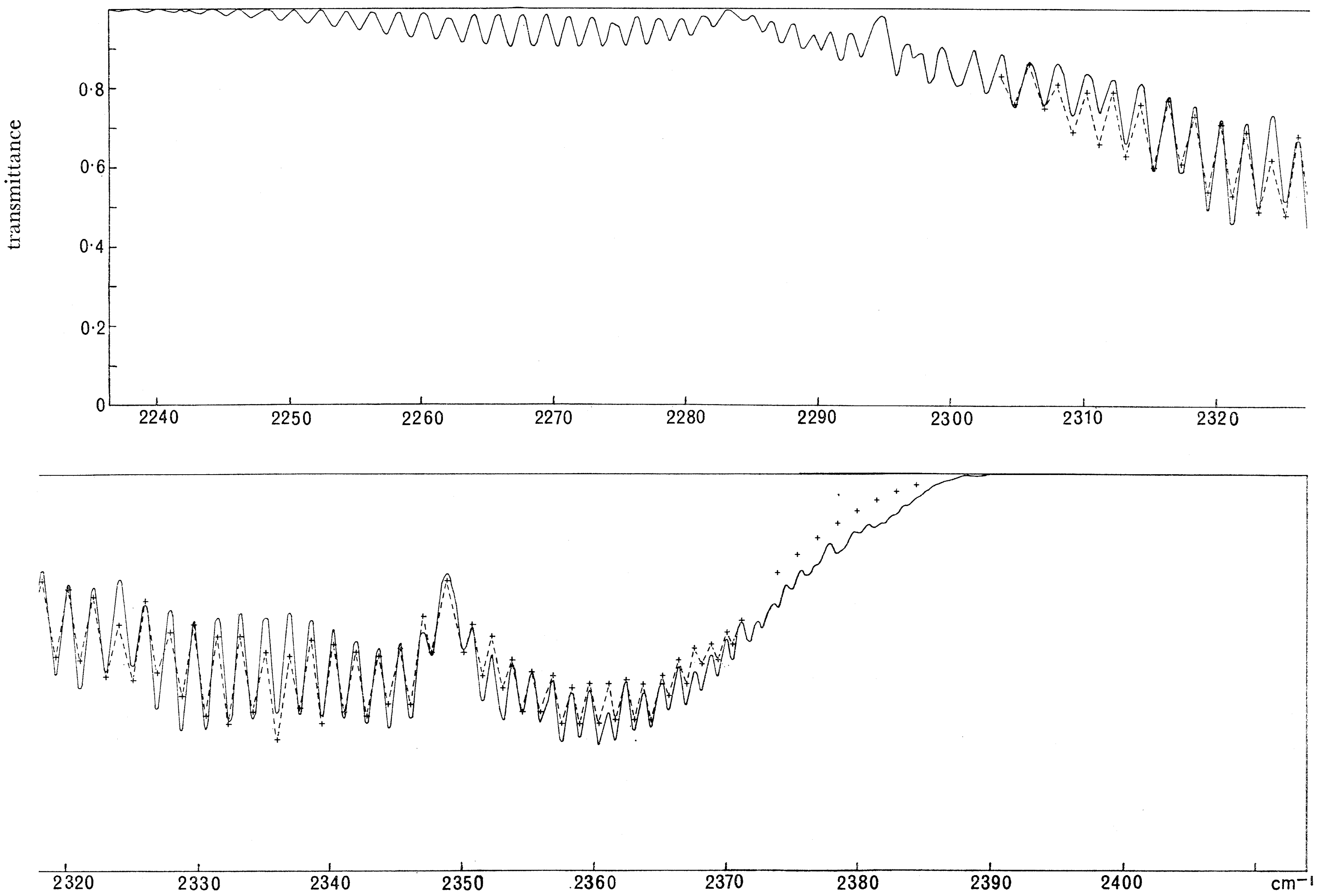

FIGURE 7. Comparison between experimental and theoretical spectral atmospheric transmittance data for the 4·3 μm CO_2 band at an altitude of 32·0 km and a solar elevation of 43·46°. —, Calculated Lorentz line; +, experimental.

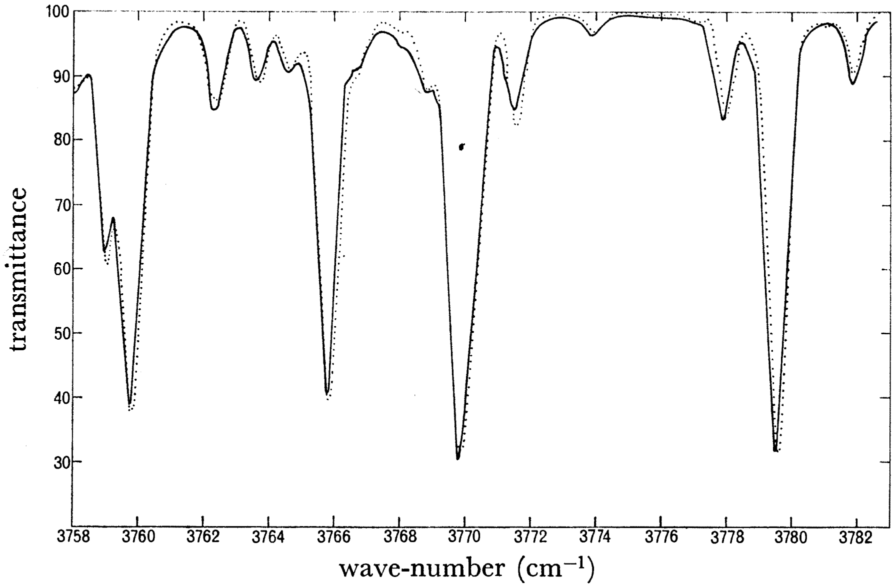

FIGURE 8. Comparison between experimental and theoretical laboratory spectral transmittance data for the H_2O absorption in the 3770 cm^{-1} region.

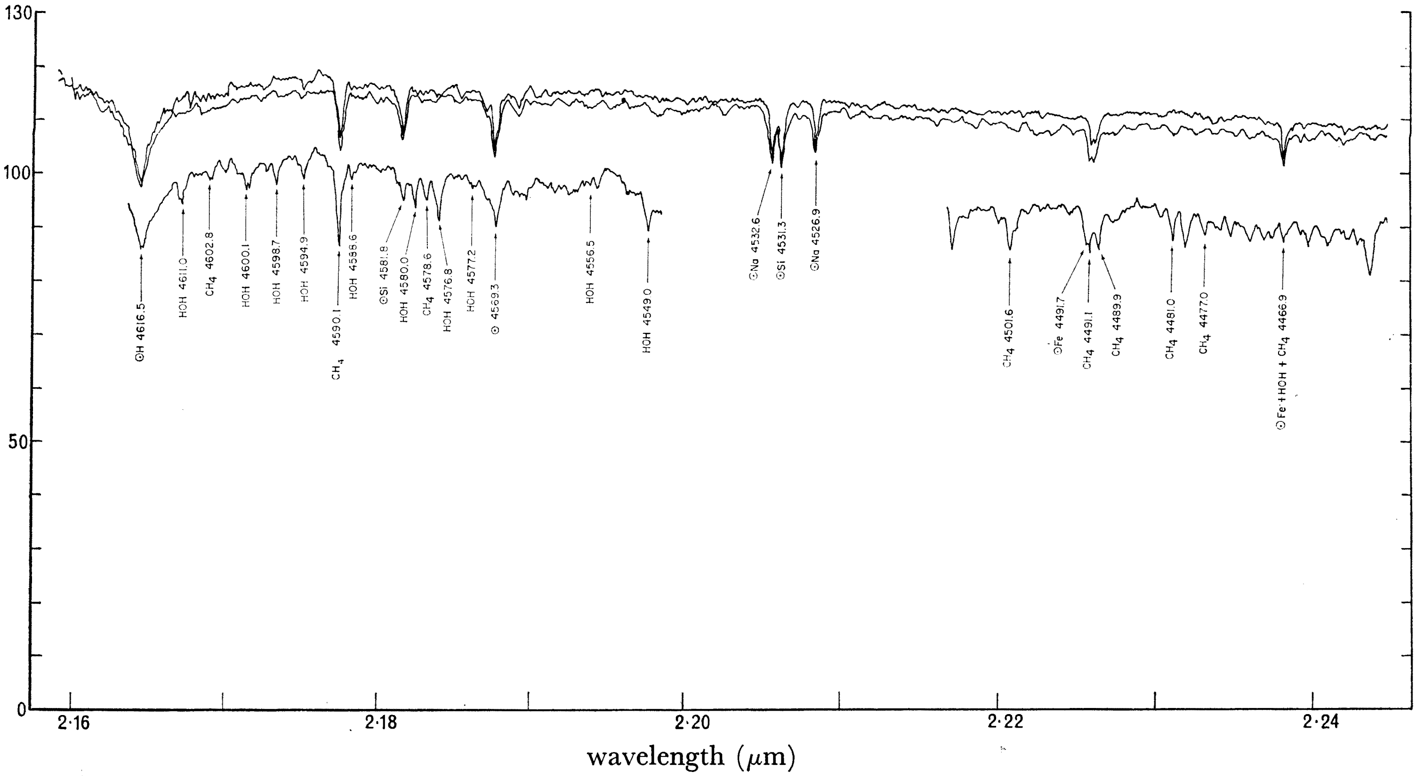

FIGURE 9. Spectral radiance of the solar disk as observed at altitudes of 4, 22 and 30 km.

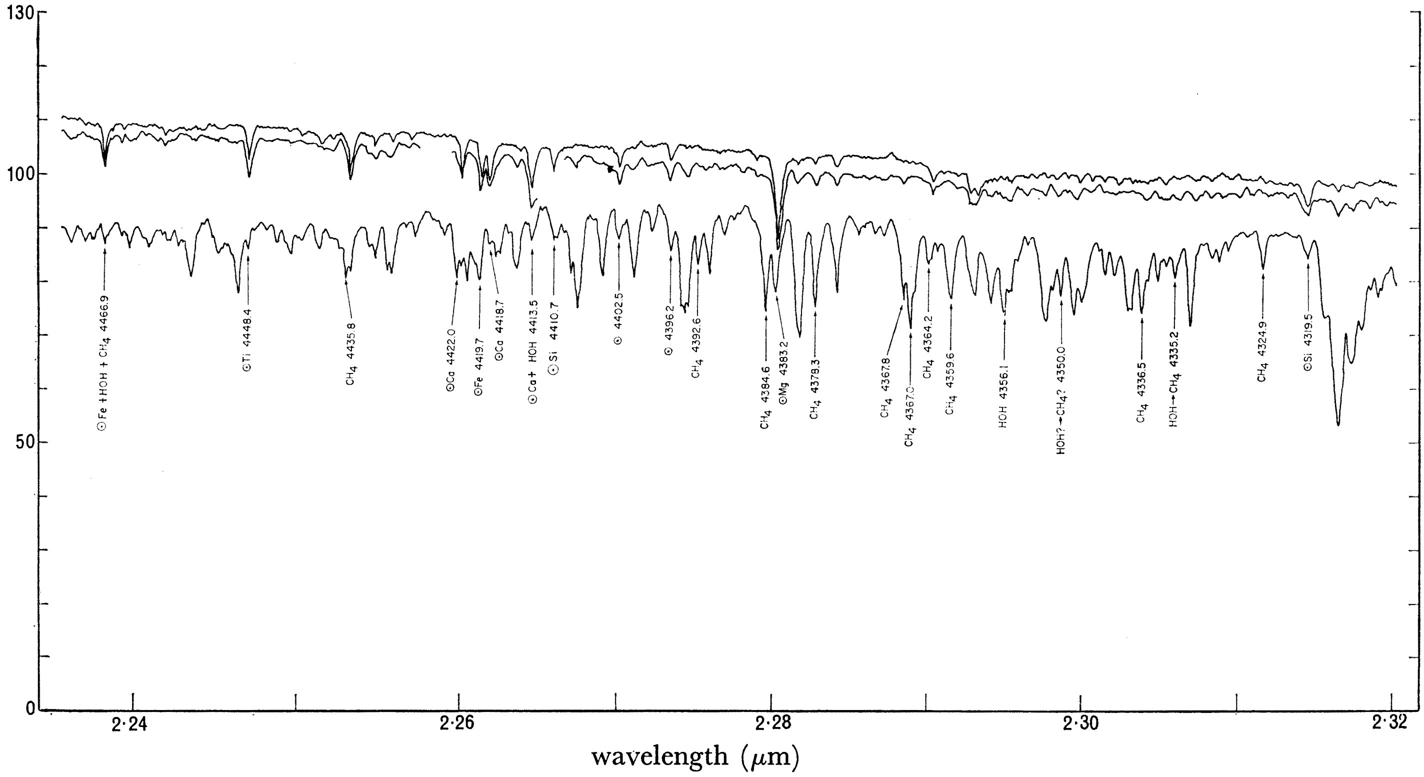

FIGURE 10. Spectral radiance of the solar disk as observed at altitudes of 4, 22 and 30 km.

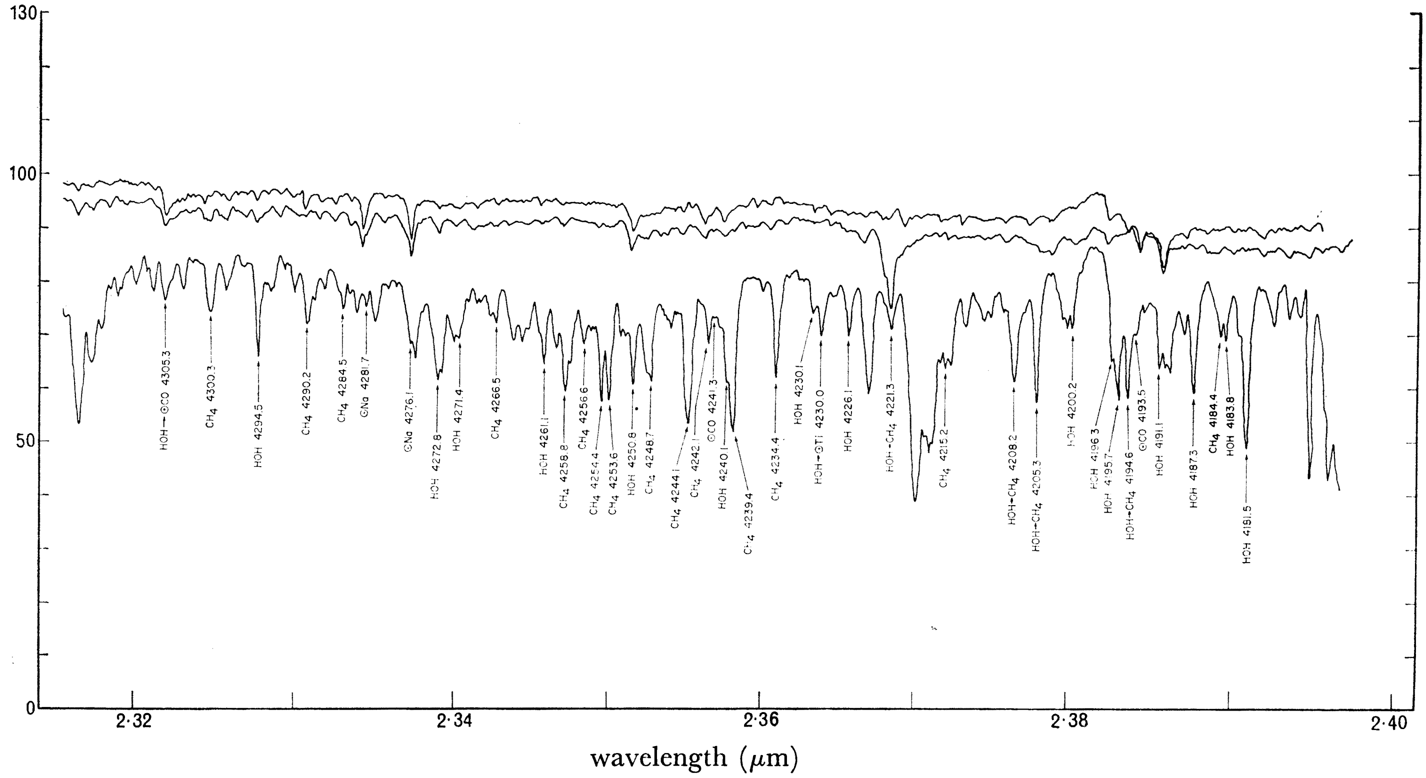

FIGURE 11. Spectral radiance of the solar disk as observed at altitudes of 4, 22 and 30 km.

Note that there is a significant change in intensity with altitude even though this is considered to be a 'window'. The identification of the various lines is based on those given in the 'Michigan' Atlas (Mohler, Pierce, McMuth & Goldberg 1950). There are a few lines which were listed in the atlas as being atmospheric which are still present at floating altitude and are obviously solar. In comparing the two high altitude records in these figures one at first attributes the difference to 'noise'. On closer examination it is found that the differences in some regions are due to the difference in absorption between the two altitudes of the numerous CH_4 lines which are present in this region. There are a number of solar CO lines present in the region from 2·29 to 2·39 μm which can be distinguished from the noise level by comparison with high temperature laboratory CO spectra. The peak in the radiance curve at 2·4 μm does not appear to be instrumental.

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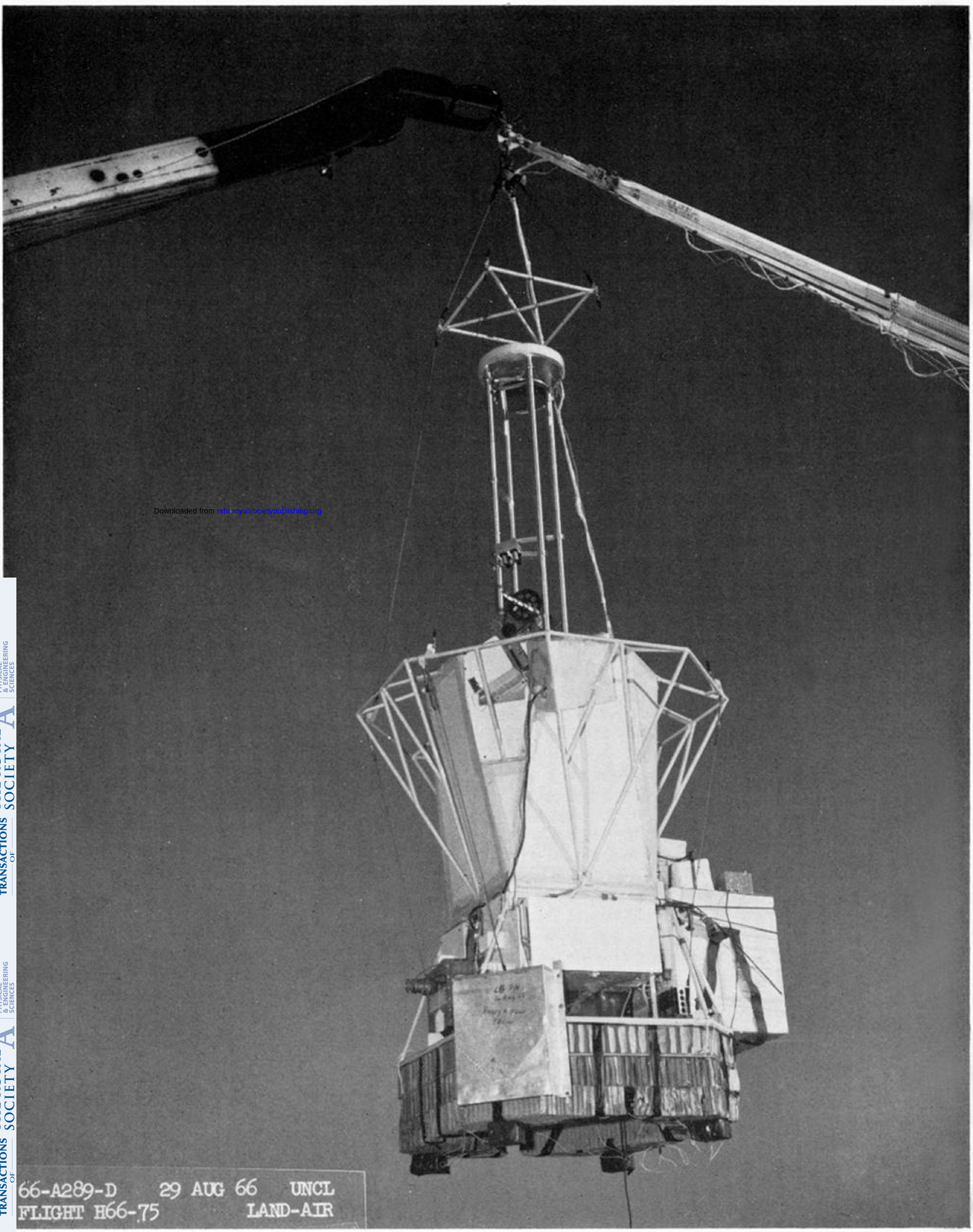

Figure 2. Photograph of the balloon payload in flight configuration.