INFRA-RED SPECTRA OF STARS, PLANETS AND THE MOON FROM STRATOSCOPE II

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Résumé. — *On a mis en œuvre deux fois le télescope Stratoscope II porté par un ballon en vue d'études spectroscopiques dans l'infra-rouge. On donne ici un résumé des résultats d'observations d'étoiles froides, de Mars, de Jupiter et de la Lune.*

Abstract. — *Two flights of the balloon borne telescope Stratoscope II have been made for infra-red spectroscopic observations. The paper summarises the results of observing cool stars, Mars, Jupiter and the Moon.*

Резюме. — Два раза был использован телескоп Стратоскоп II, несомый воздушным шаром с целью спектроскопических исследований в инфракрасной области. Здесь дано резюме результатов наблюдений холодных звезд, Марса, Юпитера и Луны.

Introduction

The 1-14 μ region of the infra-red has been partially explored from the ground. Absorption bands of the earth's atmosphere obliterate about one half of this spectral region which contains most of the thermal emission of bodies inside the orbit of Mars, and most of the emission of stars of K5 and later spectral types. It is the region of the strongest rotation-vibration bands of many molecules.

Spectra of stars, planets and satellites are needed free of terrestrial absorption because the terrestrial absorption may be covering important spectral features in these objects. However the spectral region has been inadequately studied from the ground to date, so that the observations from above the atmosphere described here also show certain features that could have been observed from the ground.

Stratoscope II is a radio controlled 36-inch telescope, operated at 80,000 ft., suspended from a balloon. Two flights in 1963 were used to make infra-red spectroscopic observations. The first flight has been described by Danielson (1963), whilst the second flight has been summarized by Woolf, Schwarzschild and Rose (1964). In both flights a prism spectrometer was used, with typical resolution 0.1 μ. In the second flight the range was from 0.9 — 3.1 μ. The first flight was a marginal success, Mars alone being observed. The second flight was nearly perfect, and we observed 1 hot star, 3 red giants, 2 red supergiants, 2 long period variables, Jupiter and the Moon.

The absorption bands

The most remarkable absorption bands observed were the H_2O bands in cool stars. In the spectrum of Mira at minimum light (M9) Figure 1, the bands at 1.4, 1.9 and 2.7 μ absorb 1/4 to 1/3 of the energy under the continuum. These bands increase rapidly in strength with decreasing temperature. They are not visible in Aldebaran (K5III) Figure 2, are barely visible in μ Geminorum (M3III), moderately strong in ρ Persei (M4II-III), and strong in R. Leonis (M8). The bands are strongly luminosity dependent, and are about twice as strong in Betelgeuse (M2-31 *ab*) Figure 3, as in μ Gem, and about twice as strong in μ Cephei (M2I*a*) as in Betelgeuse. For the case of Mira, we have shown that the strength of the bands is roughly consistent with the amount of water predicted to be in its atmosphere. The strength of the bands in the supergiants is surprising, but is more likely due to turbulent broadening of lines than to an excessive amount of water.

The wings of these bands can be seen from the ground (Kuiper 1963), (Sinton and Boyce 1964). The unadulterated spectrum from balloon altitude permitted confirmation of the identification. It also permitted quantitative assessment of the strength of the bands, and their variation with spectral type and luminosity.

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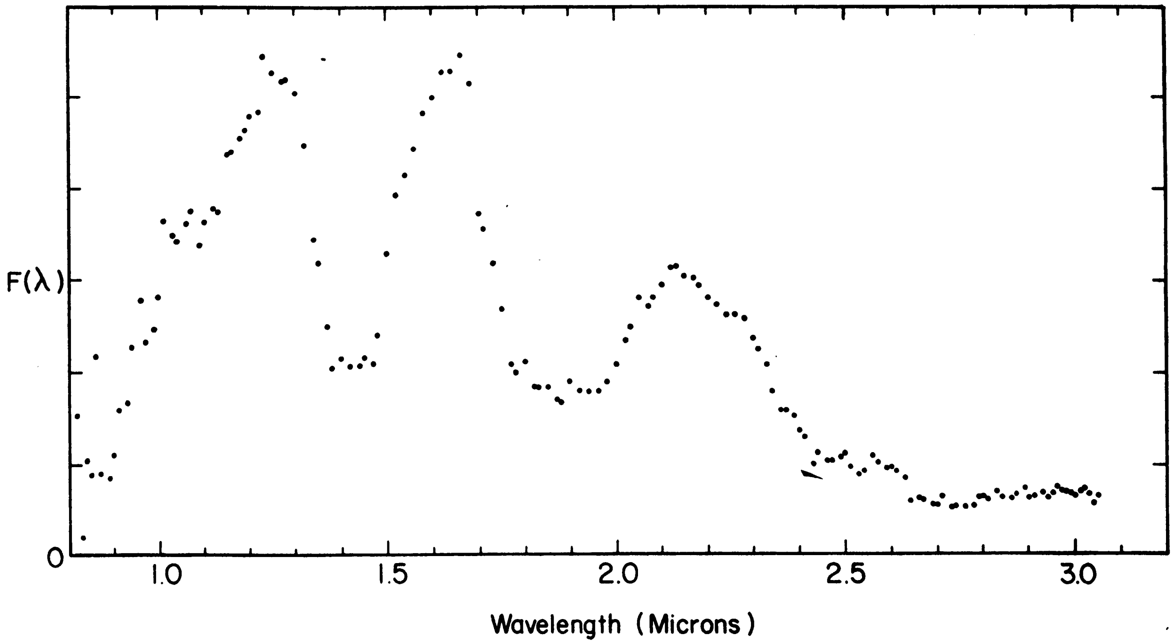

Fig. 1. — Infra red spectrum of Mira.

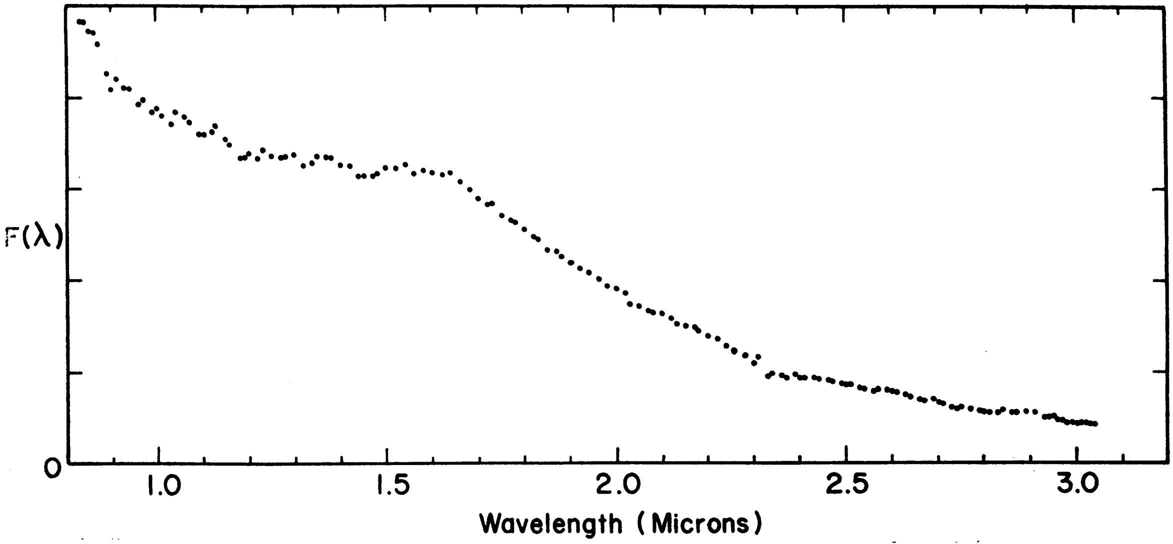

Fig. 2. — Infra red spectrum of Aldebaran.

A search was made for an absorption band of interstellar ice (Danielson, Gaustad and Woolf 1965). The supergiant μ Cephei suffers heavy obscuration and the differential interstellar reddening between it and Betelgeuse is approximately Δ B-V = 0.4 magnitudes. A broad band at 3.1 μ should be produced by interstellar H_2O ice if it exists in quantity. We have assumed that the interstellar particles have a size distribution that gives a good fit to the interstellar reddening variation, assumed that the particles are pure H_2O ice, and calculated the strength of the band (Fig. 4). This figure shows the spectrum of μ Cephei divided by Betelgeuse. The dotted continuum is predicted from the estimated differential reddening. The stronger dotted band at 3.1 μ is the predicted band. The weaker band is our estimated upper limit to the strength of the band, and corresponds to 1/4 of the predicted amount of ice. The inset shows two possible alternative ways of reducing the data. These are likewise incompatible with pure ice, and mar-

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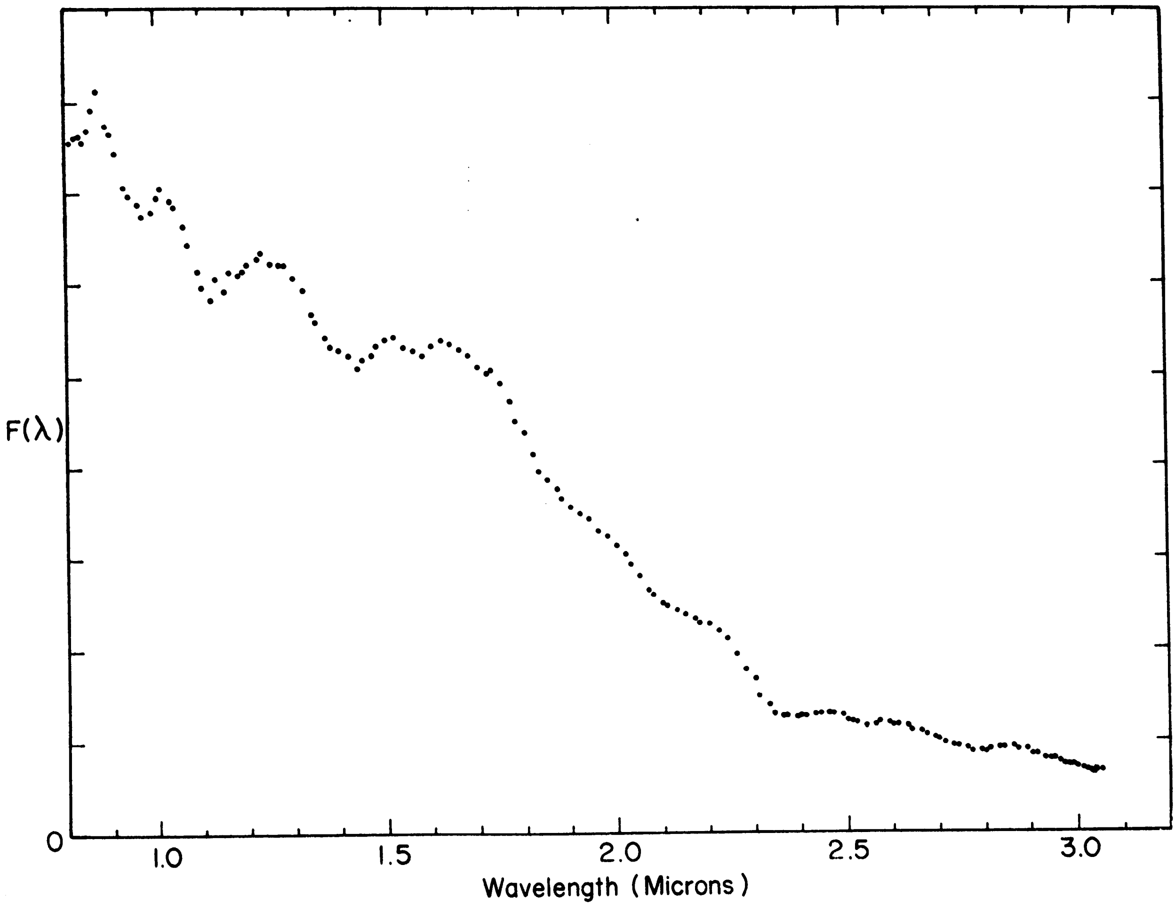

FIG. 3. — Infra red spectrum of Betelgeuse.

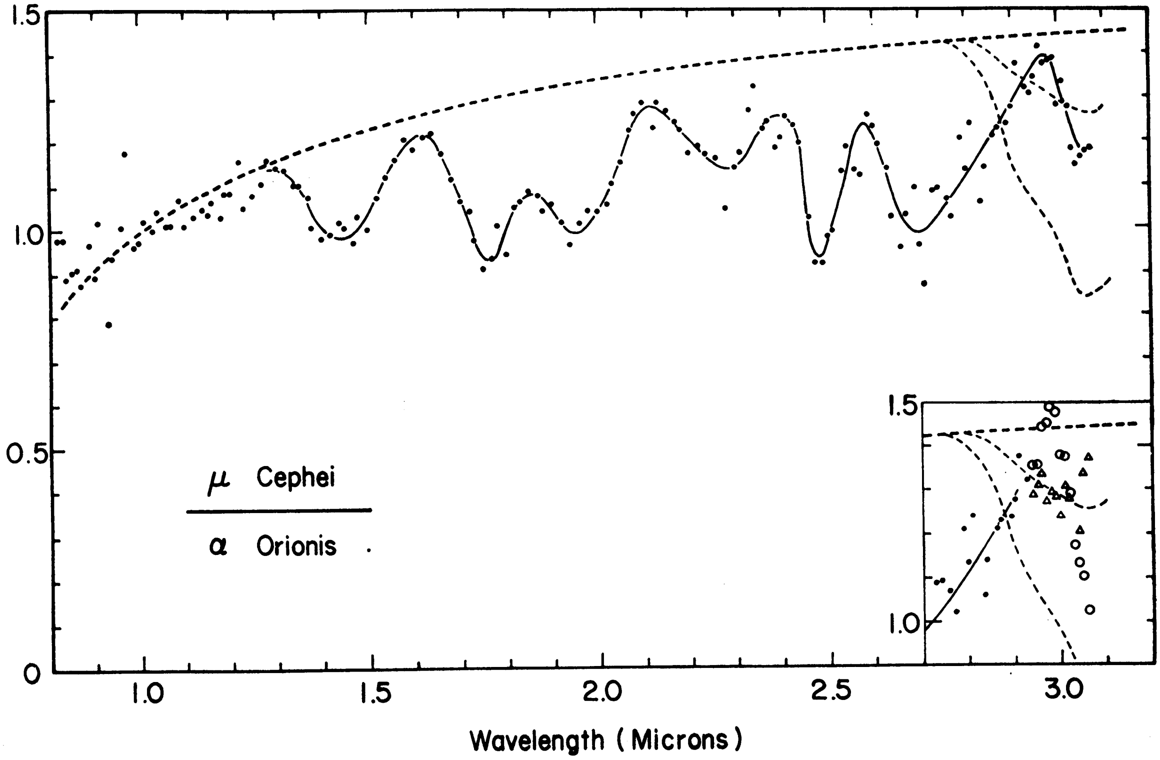

FIG. 4. — The absence of the interstellar ice band in the spectrum of μ Cephei.

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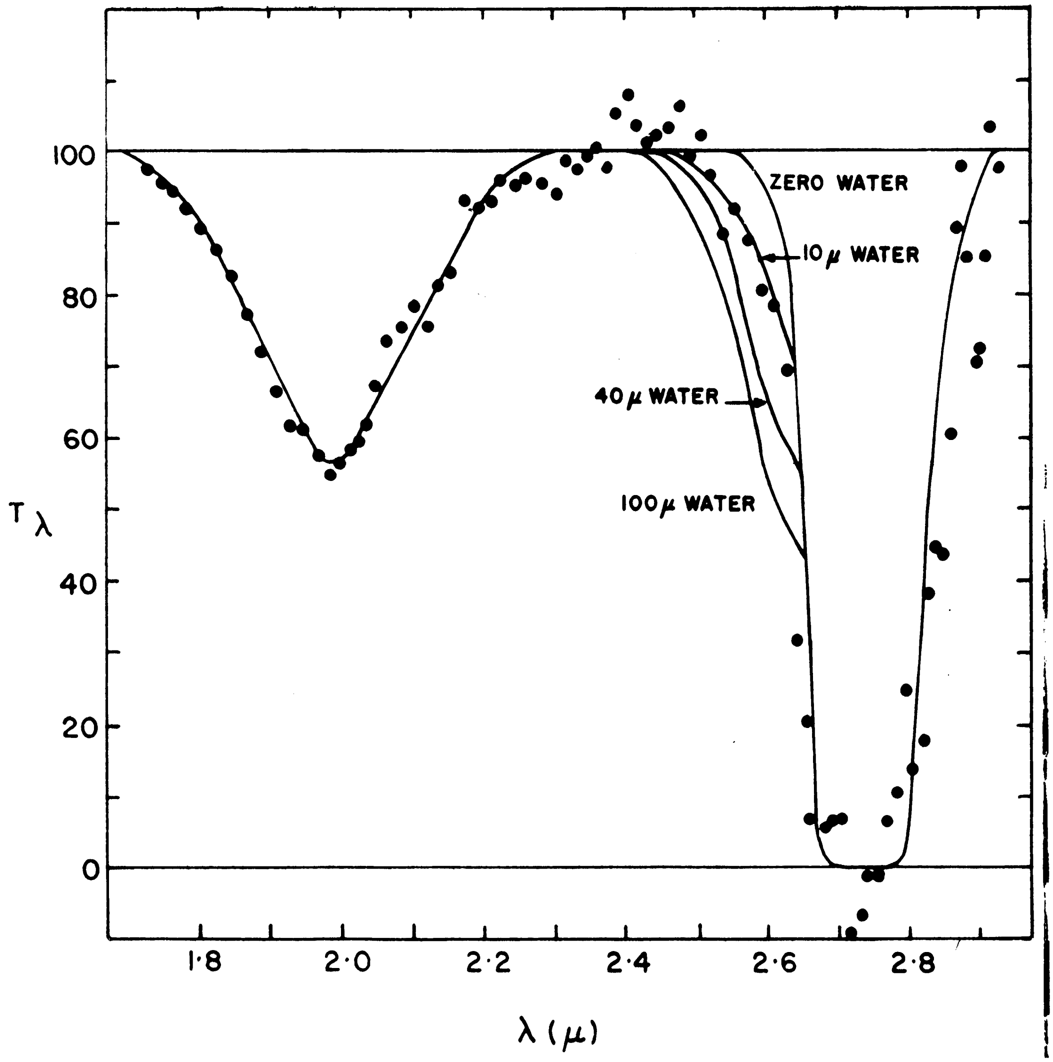

Fig 5. — Part of the infra red spectrum of Mars.

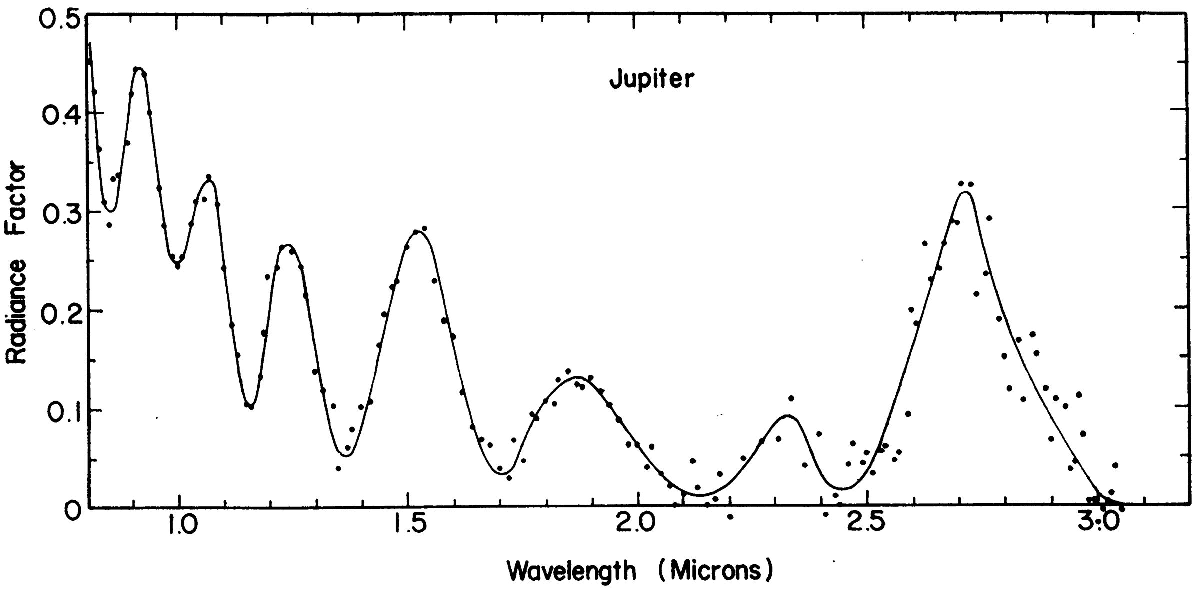

Fig. 6. — Infra red spectrum of Jupiter.

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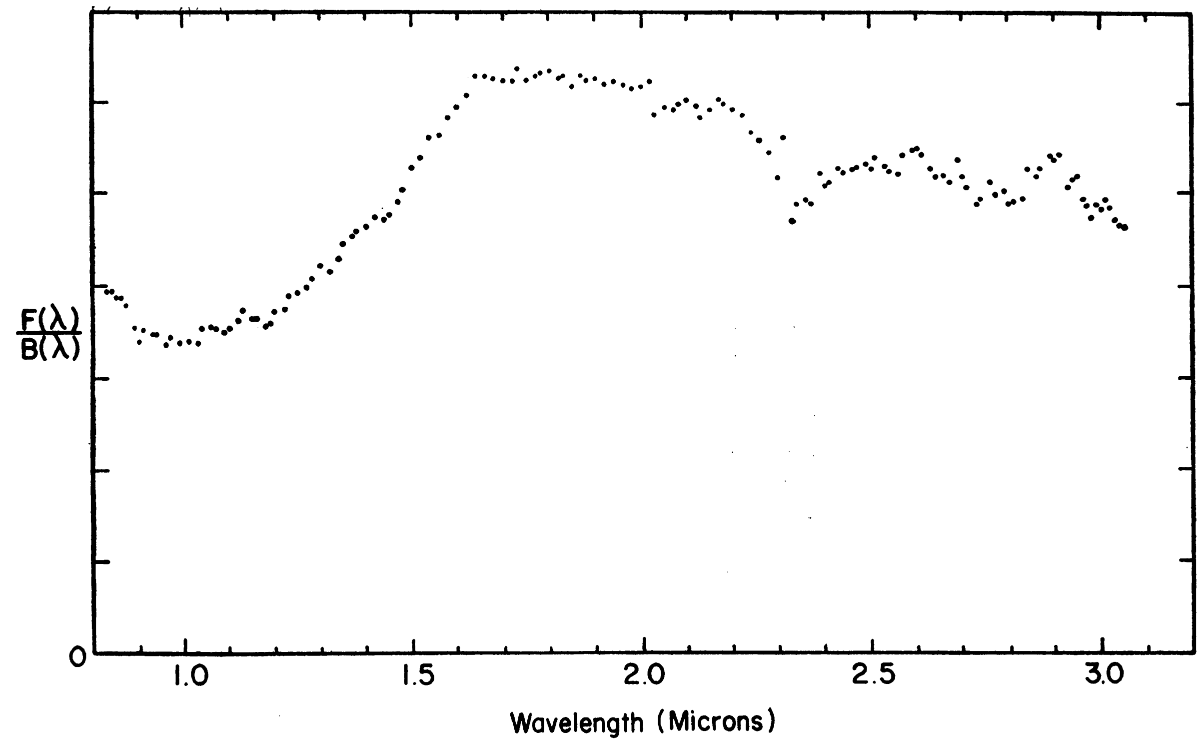

FIG. 7. — Spectrum of Aldebaran divided by a 3500 °K black body.

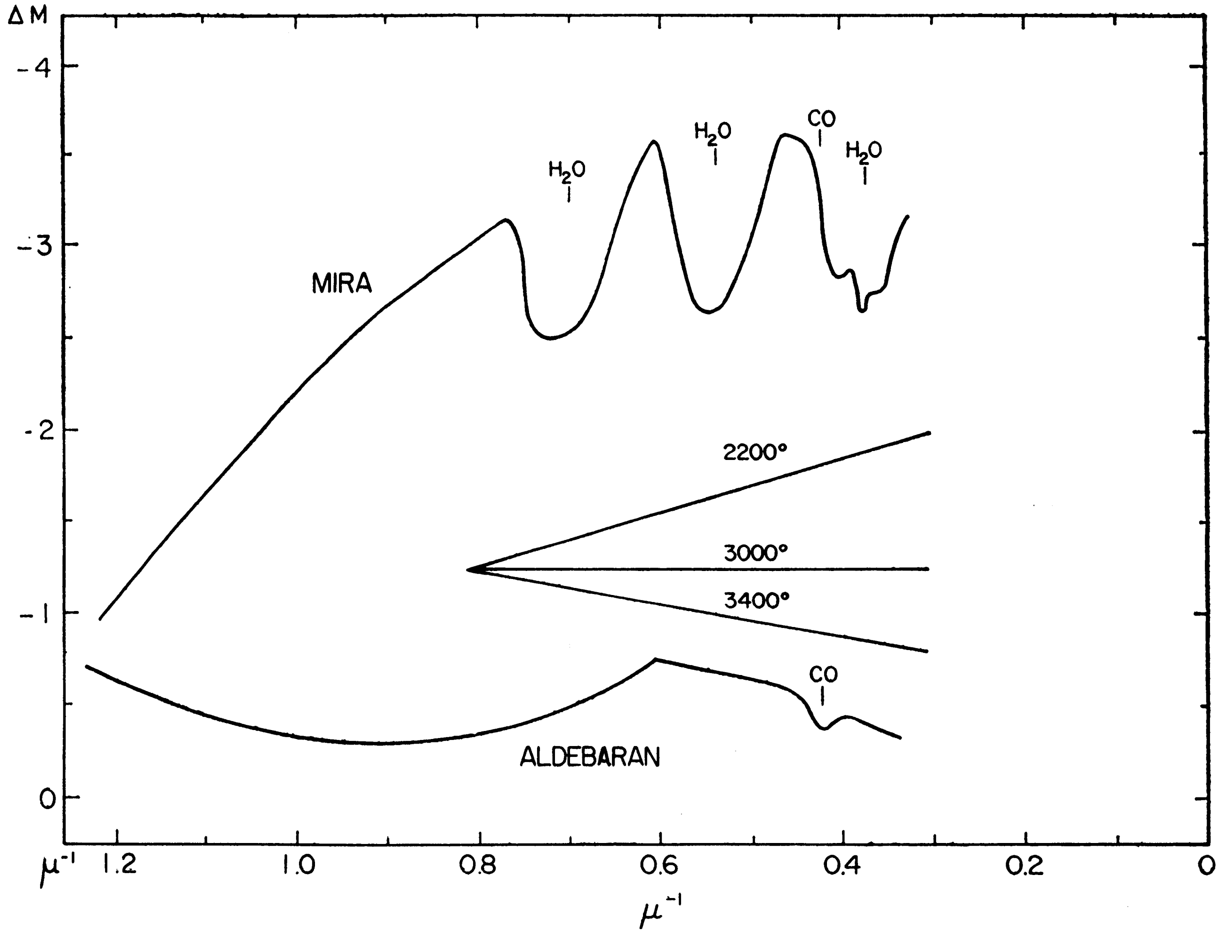

FIG. 8. — Deviations from a black body for Aldebaran and Mira.

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ginally consistent with 1/4 of the absorption being produced by ice. The result depends upon assumptions about the behaviour of ice that should be modified for dirty ice at low temperatures and so must be treated with caution. This problem can be studied from the ground. If a star with H_2O absorption more similar to that in μ Cephei is used for comparison, the band will either be detected, or the upper limit on its strength will be improved.

In the Martian spectrum, a strong band was discovered at 2.7 μ (Danielson, Gaustad Schwarzschild, Weaver and Woolf 1964), The breadth of this feature is too small for it to be caused by water vapour, and its width and strength are consistent with it being predominantly CO_2 (Fig. 5). Upper limits to the amount of water in the Martian atmosphere were obtained from this band, and also from the weakness of the 6.3 μ band. The result was confirmed and superceded by ground based observation of the 0.84 μ band of H_2O in the Martian atmosphere, doppler shifted into a clear part of the spectrum (Kaplan, Munch and Spinrad 1964). A discrepancy about the strength of the 2.0 μ CO_2 band in Mars exists between us and ground based observations of the same band discussed by these authors. Such discrepancies are known to occur when different instruments are used to make measurements of equivalent widths. At present, the easiest way of dealing with this problem is to use the same spectrograph, and artifically produce a line or band of equal strength. To date the ground based observations have proved more sensitive for H_2O on Mars, and less sensitive for stars. However the infrared observations of planets should be continued from above the atmosphere. These observations are needed to study the heat balance of planets. The heat balance depends, directly on the strength of certain infra red bands but only indirectly on the strength of the short wavelength bands.

Returning to the Stratoscope II observations, the band spectrum of Jupiter has so far shown no great surprises (Danielson 1965). The spectra from the ground are difficult to interpret, because the chopped-up spectrum of Jupiter (Fig. 6) is further chopped up by terrestrial absorption. Beyond 1.7 μ, Jupiter tends to radiate only where the earth's atmosphere absorbs strongly. The bands at 0.85, 0.99, 1.16, 1.37 and 1.7 μ are mainly produced by CH_4. The band at 3.0 μ is produced by NH_3. The broad band at 2-2..5 μ is probably caused by the CH_4 bands at 2.20, 2.32, 2.37 and 2.42 μ and also the pressure induced dipole absorption of H_2. The nature of this band has become apparent because the band edges were previously hidden by terrestrial absorption. However all of these molecules have previously been detected at shorter wavelengths.

The continua

Studies of continua can be made from the ground using the atmospheric windows. However as little work has been done in this field, Stratoscope II observations (made mainly for other purposes) have been used for these studies. The observations aloft have some advantages in that there are no uncertainties about how to allow for extinction in the infra-red, and there is a complete record of the continuum rather than a few isolated points.

In the atmospheres of cool stars there is a window at 1.65 μ where the opacity becomes very low. This window has been observed from the ground in the Sun (Pierce 1954). It has not shown in current photometric observations (e. g. Johnson 1962), because the photometric system is not using the 1.6 μ terrestrial atmospheric window. This omission is unfortunate as a study of the emission through the stellar window as it varies with spectral type, luminosity, and metal abundance may show some surprises. The Stratoscope II results show the appearance of the window in Aldebaran, Figure 2. It is better seen in Figure 7 where the spectrum of Aldebaran has been divided by a 3500° black body. The deviations from a black body spectrum amount to a factor of about 1.5.

A surprising result of the observation of the two long period variables is that even ignoring the H_2O absorption, their spectra are very poorly described by black bodies. They emit far too little radiation at short wavelengths. The deviations from a black body amount to a few stellar magnitudes by 0.5 μ. From the ground these deviations have been demonstrated by Low and Johnson (1964) in χ Cygni. Figure 8 (Stratoscope II results) shows spectral energy curve against a 3000° black body for Mira at light minimum and also for Aldebaran. In this figure a black body is a straight line to sufficient accuracy. It would be valuable to confirm whether the short wavelength energy deficiency also appears in the regions where there are no TiO bands at wavelengths between 0.5 and 1 μ.

The continuous reflection spectrum of the Moon is being studied by Danielson and Wattson (1965). They find a smoothly increasing radiance from 0.8 to 2 μ. The result is probably more an indication of the state of division and the radiation damage of the lunar surface than a guide to its chemical composition. The radiance factor is so high at 2 μ that ground based photometric studies of the phase variation at this wavelength should be made. This variation may well differ from that observed at shorter wavelengths. Beyond 2 1/2 μ the thermal radiation of the Moon dominated the spectrum.

In the observation of Mars, the rapid decline of the radiance factor between 2 and 3 μ, first observed by Kuiper was confirmed. Newly observed was the cross over between the reflection and emission spectrum near 4 μ as predicted.

The operation of Stratoscope II was under the direction of Martin Schwarzschild. Remote control of the telescope and scientific decisions during the flight were by Robert Danielson. The results described here are the result of the enthusiastic cooperation of several agencies and companies, and many individuals. In this paper I have attempted to summarize the results of our joint efforts. Stratoscope II is sponsored by NSF, ONR, and NASA.

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Discussion

O. Gingerich. — I believe that some of the motivations for these observations arose from the theoretical model atmospheres computed by Kumar and myself for cool stars. The optical window at 1,65 μ is bounded on the short wavelength side by a (H^-) and, for the coolest models, on the long wavelength side by a (H_2^-). On a model of 2500 °K effective temperature, over 99,9 % of the hydrogen is in a molecular form. The opacity window agrees closely with the maximum of the Planck function and consequently, the predicted spectra show unusually sharp peaks at 1,65 μ. These are not fully shown in the observations because of the molecular bands. Since these bands are also important in the terrestrial atmosphere, a considerable amount of information is available on them and thus, I plan to include them in the computer program for a second approximation in a hope to match the Stratoscope observations more fully.