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BOUNDARY LAYER INTERFERENCE CALCULATIONS

FINAL REPORT

G.M. Daniels, L.A. Popper, K.L. Wray, et al.

AVCO EVERETT RESEARCH LABORATORY

JULY 1971

jointly sponsored by

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FOREWORD

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This research was supported by the Advanced Research Projects Agency of the Department of Defense and Space and Missile Systems Organization, Air Force Systems Command and was monitored by Space and Missile Systems Organization, Air Force Systems Command under Contract F04701-71-C-0033. The Air Force program monitor for this contract is Capt. M. Anderson, USAF, Project Officer, Environmental Technology Branch, RNSE.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions; it is published only for the exchange and stimulation of ideas.

Capt. M. Anderson
Project Officer,
Environmental Technology Branch,
RNSE

ABSTRACT

This is a final report on Avco Everett Research Laboratory's study on "Boundary Layer Interference Calculations." This special task was carried out under Contract No. F04701-71-C-0033. In this program the infrared radiation from 3 - 20 μ emanating from the ablating boundary layer of a reentering vehicle was calculated down to 100 kft. It was found that the radiation was dominated by ambient CO_2 and H_2O and air shock produced NO down to 150 kft at which altitude ablation product radiation began to become important. The results of these calculations were compared with various sources of "earth" radiation including earth surface, atmosphere, and scattered sunlight. CO_2 radiation at 4.3μ from the boundary layer was found to have a higher radiance than the "earth" at 100 kft.

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I. INTRODUCTION

In this task we have calculated the infrared radiation emanating from the boundary layer at the end of a reentering conical vehicle. The altitude regime considered was from early reentry down to 100 kft and the wavelength regime was 3 - 20 μ. Both ambient and ablative species were included in the calculations. These boundary layer results were compared to calculated earth radiance which included earth surface radiance, atmospheric radiance, scattered sunlight and atmospheric absorption.

II. EARTH AND ATMOSPHERIC RADIANCE

The infrared radiance in the 3 - 20 μ region seen by a sensor looking downward from 100 kft or more above earth's atmosphere will have three components: (1) the thermal radiation from earth's surface after attenuation by the atmosphere, (2) the thermal radiation from the atmosphere itself, and (3) scattered solar radiation, primarily from earth's surface seen during daylight at wavelengths less than 5 μ. The sum of the attenuated radiation from earth's surface and the atmospheric radiation is called earthshine; it is the total thermal radiation seen by a sensor. The solid curve in Fig. 1 shows the detected thermal radiation from earth's surface, calculated by multiplying the radiance of a blackbody at 285^{o}K and the transmission of a standard atmosphere obtained from the AFCRL atmospheric transmission program.[1] The earthshine

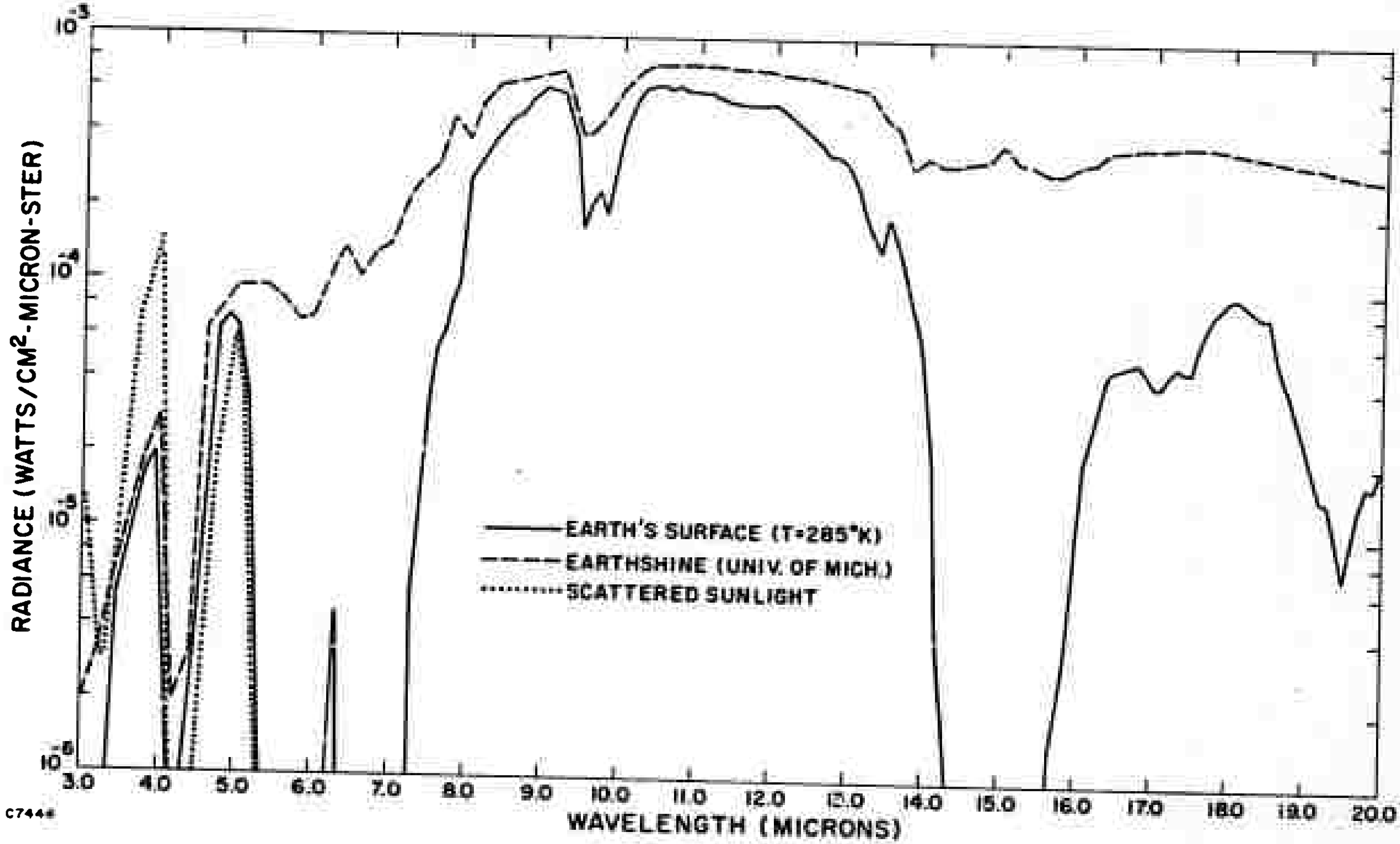

Fig. 1 Radiation intensity from various "earth" sources as seen looking straight down from an altitude above 100 kft.

(dashed curve) in the 5 - 20 micron region was obtained directly from calculations made at the University of Michigan[2]; an AERL calculation extended the results to the 3 - 5 micron region. The scattered sunlight, given by the dotted curve, was estimated by multiplying the vertically incident solar flux[3] by two-way atmospheric transmission and assuming earth's surface acts as a Lambertian reflector with a reflectance of 0.25. This estimate should give an upper limit to the scattered sunlight contribution; diurnally averaged values should be much lower. The spectral resolution of the calculations is about 0.1 micron.

Figure 1 shows that the 8 - 14 μ region is to be preferred for making observations of the earth's surface, if minimum interference from absorption, thermal emission from the atmosphere, and scattered sunlight is desired. The 3 - 5 μ region is marked by scattered sunlight or CO_2 absorption, H_2O absorbs in the 5 - 8 μ region, CO_2 absorbs in the 14 - 16 μ region, and H_2O absorbs from 16 to 20 μ. A 10 - 12 μ channel looks very good. At 11 μ, for example, the earth's surface has a radiance of 8×10^{-4} watts/ster-cm^2-μ and the atmospheric transmission is 75% yielding a transmitted radiance of 6×10^{-4}, as shown in Fig. 1. The total earthshine is given as 7.6×10^{-4}; subtraction (somewhat risky because the numbers come from different sources) yields 1.6×10^{-4} watts/ster-cm^2-μ for the thermal emission from the atmosphere. This leads to a ratio of received signal to background of $6/1.6 \simeq 4$.

III. BOUNDARY LAYER MODEL

The reentry vehicle considered in this study is shown in Fig. 2. It is a 7^{o} half angle conical R/V with carbon phenolic heat shield and ATJ-S graphite tip having a nose radius of 0.5" and reentering at a relatively slow velocity of 16,900 feet per second.

For altitudes of interest in this study, the relatively slow reentry velocity makes the primary source of ablation products the pyrolysis of the carbon phenolic heat shield. Detailed ablation calculations were carried out[4] and the resulting mass flux, integrated over the body, is given in Fig. 3. Interaction of the CP heat shield ablation products with air leads to the IR radiating molecules CO, CO_2, H_2O and OH. Furthermore, clean air chemistry produces NO. We also considered the effects of ambient CO_2 which is present in air to 330 ppm concentration and water whose concentration at high altitudes is somewhat controversial but we used 16 ppm as a nominal value.

Equilibrium was assumed for the air/ablating boundary layer chemistry. As we shall see ablation only dominates at 100 kft so this assumption is probably reasonable. The ambient CO_2 and water dominated the IR radiation in the boundary layer at high altitudes where, to be conservative, we assumed these species were chemically frozen. Furthermore, the vibrational temperature of all radiating species was taken to be the local translational temperature.

A local similarity model was used to calculate profiles of species

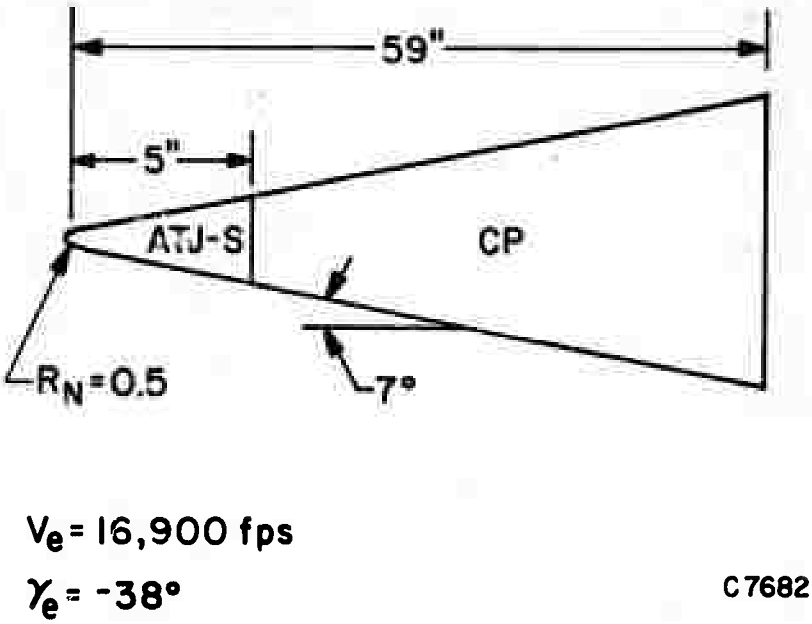

Fig. 2 Reentry vehicle and reentry parameters for which boundary layer IR radiation intensities were calculated.

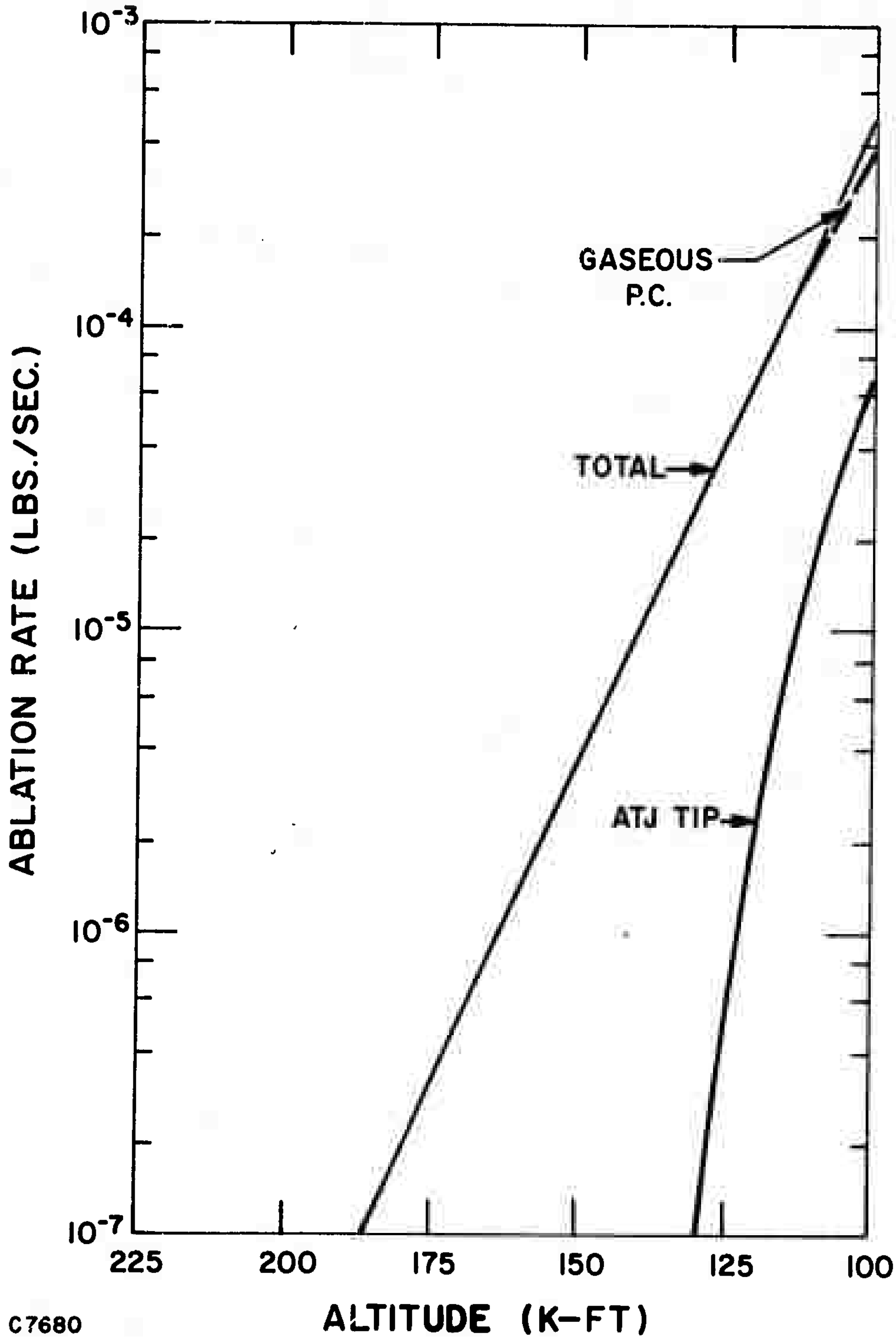

Fig. 3 Ablation rate versus altitude for the R/V shown in Fig. 2.

concentration and temperature at the end of the body. The mass flux in the ablating boundary layer was matched to detailed ablation calculations. Blasius (conservation equations) velocity profiles were employed at the end of the vehicle and then Crocco integrals were used to relate the enthalpy and ablation product mass fraction profiles to the Blasius velocity profile. Finally, individual species concentration and temperature profiles were obtained for the above enthalpy/ablation product mass fraction profiles by equilibrium computer codes. This overall boundary layer calculation technique is discussed in detail in Ref. 5. Finally, the radiation intensity for each radiating species is a known function of its local concentration and temperature, and the intensity thus evaluated was then integrated across the boundary layer.

IV. BOUNDARY LAYER RADIANCE

The spectral intensity per radiating molecule versus wavelength from 8 - 20 μ is shown in Figs. 4, 5 and 6 for CO_2, H_2O and OH radicals, respectively, for a number of different temperatures. In the near IR (from 1.5 - 6 μ) the spectral intensity of a number of radiators at 3000°K is shown in Fig. 7. The effective radiation temperature, as shown by the boundary layer calculations, is about 2500°K for CO_2, CO, NO and OH while that of water is about 2000°K.

The results of the boundary layer calculations are shown in Fig. 8 where the spectral radiance in watts/ster-cm^2-μ is shown at a number of key wavelengths versus altitude. At high altitudes the ambient CO_2 and H_2O, along with the NO formed from the high temperature air, dominates

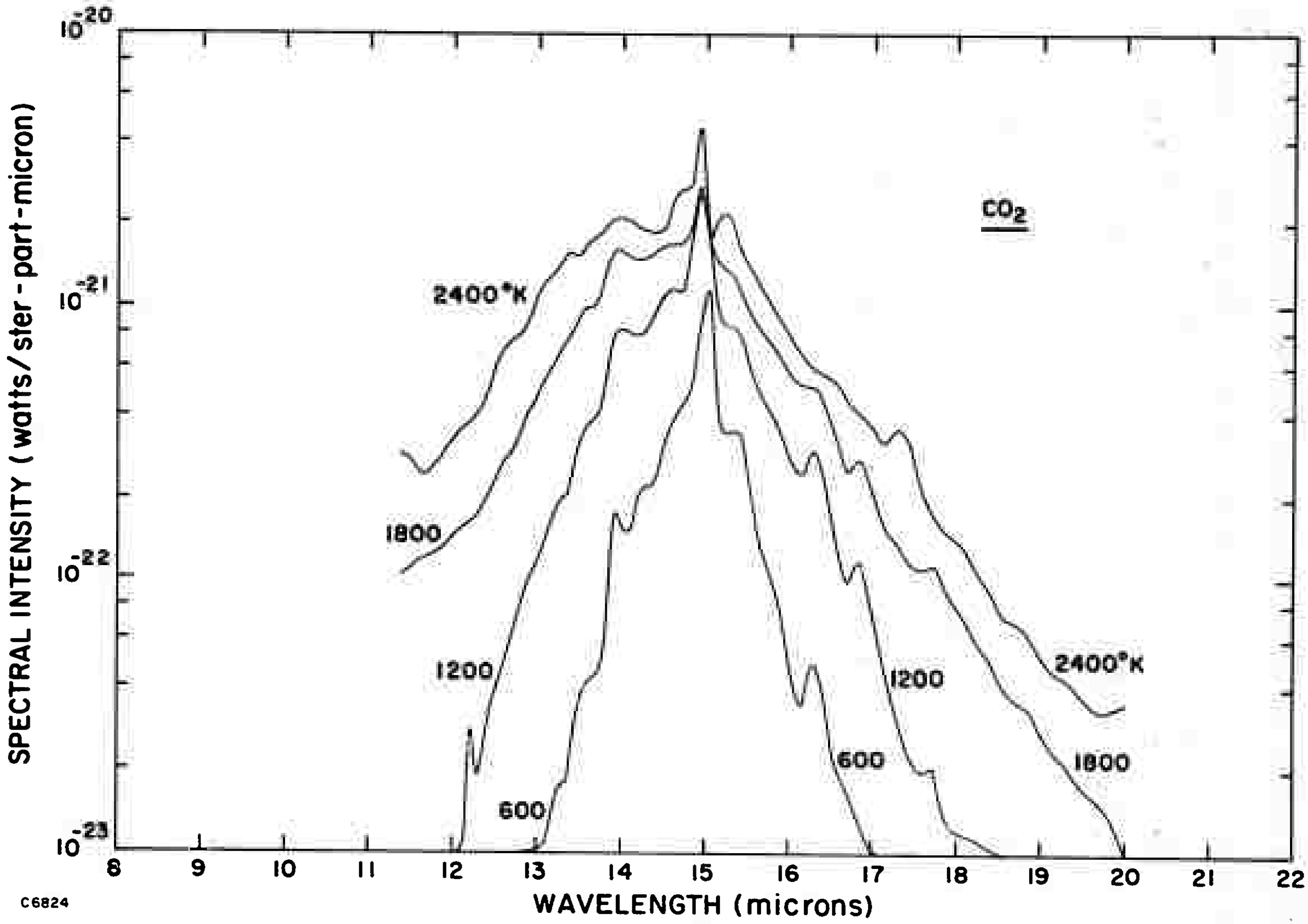

Fig. 4 Theoretical spectral intensity versus wavelength for the carbon dioxide vibrational band in the 8 - 20μ region.

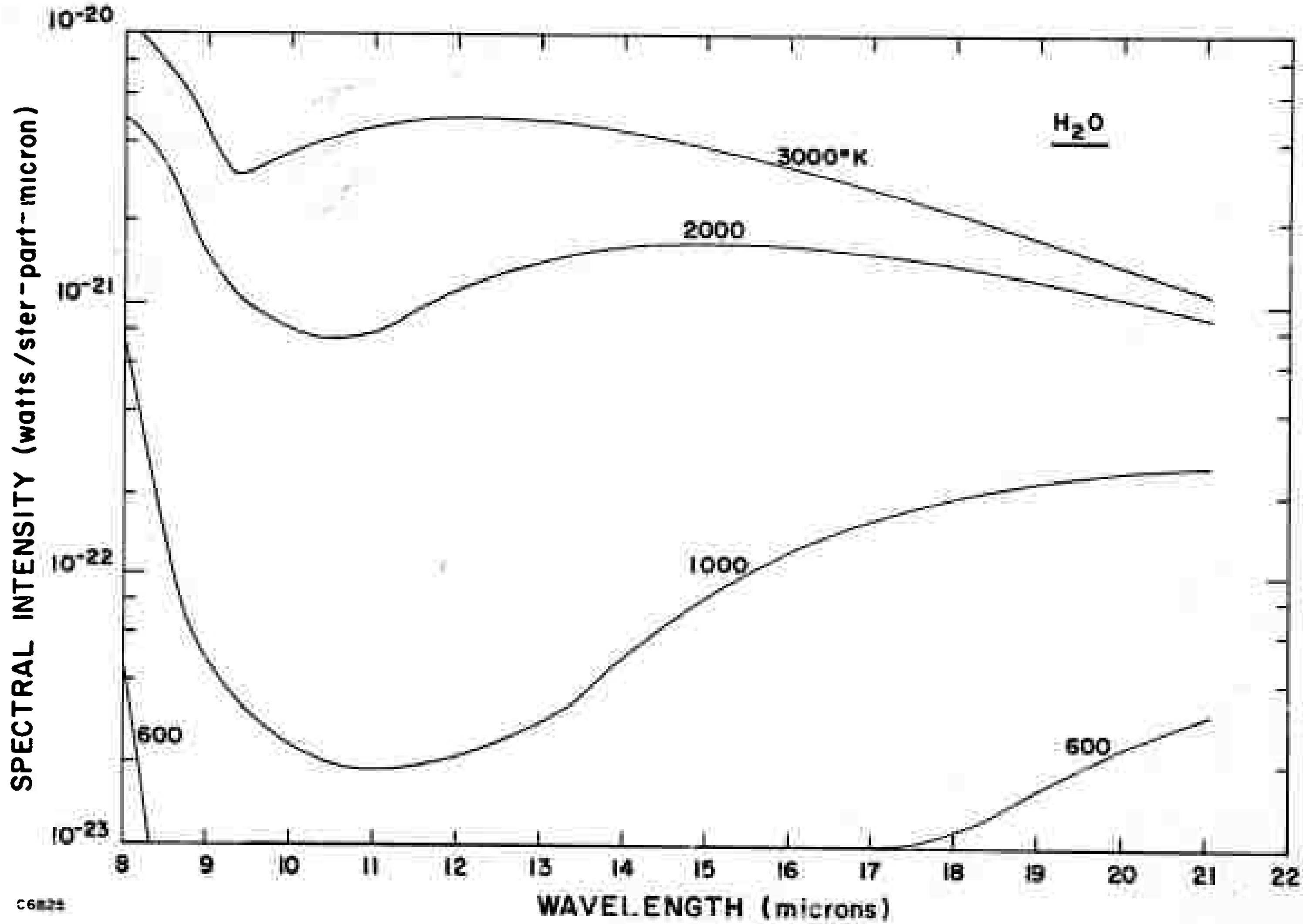

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Fig. 5 Theoretical spectral intensity versus wavelength for water in the 8 - 20μ region. The radiation includes both a vibration-rotation band and pure rotational lines.

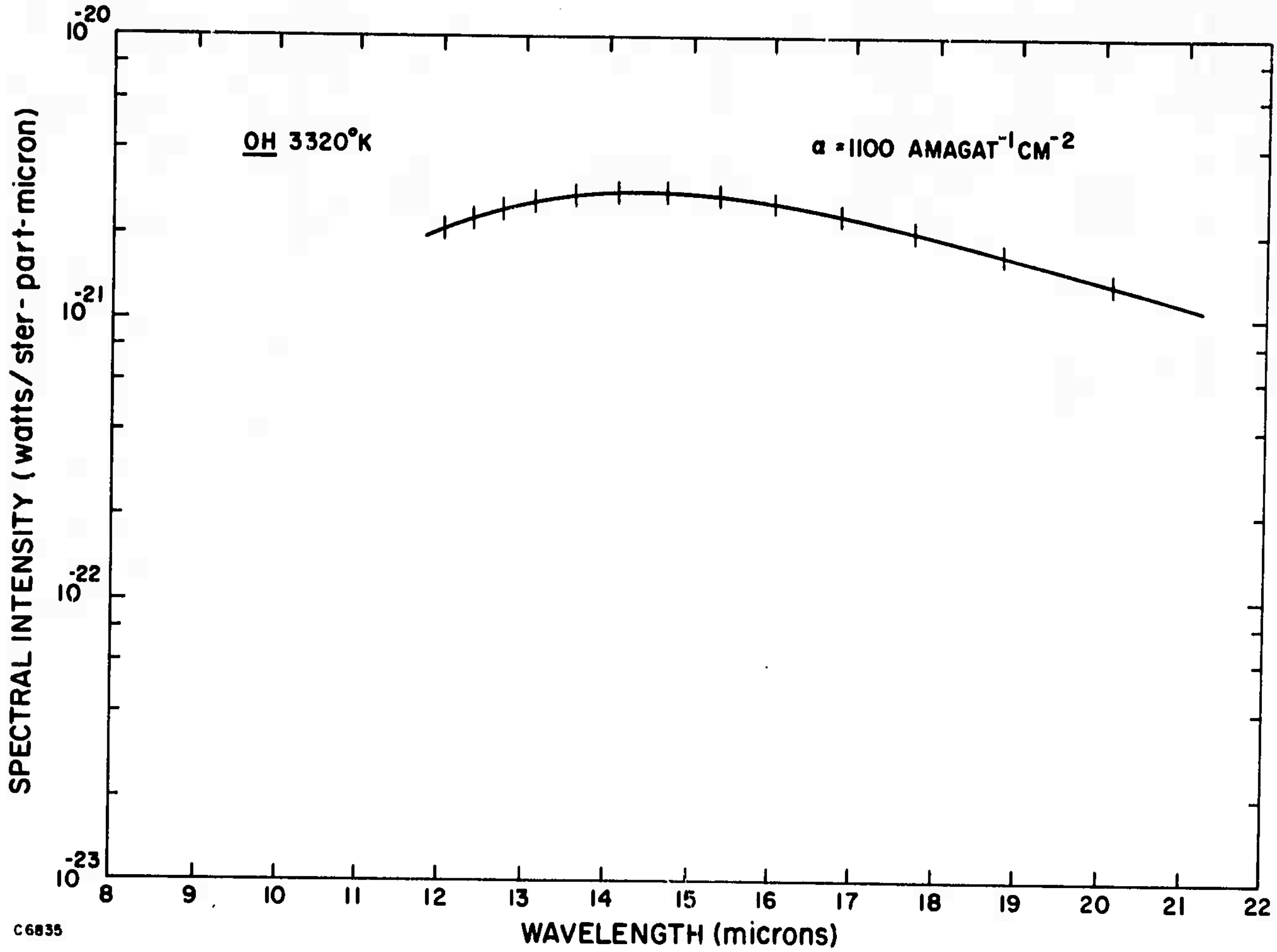

Fig. 6 Theoretical spectral intensity versus wavelength for OH radicals in the 8 - 20μ region. The tick marks indicate location of the rotational lines. The curve is averaged over an assumed band pass wide compared to the line spacing.

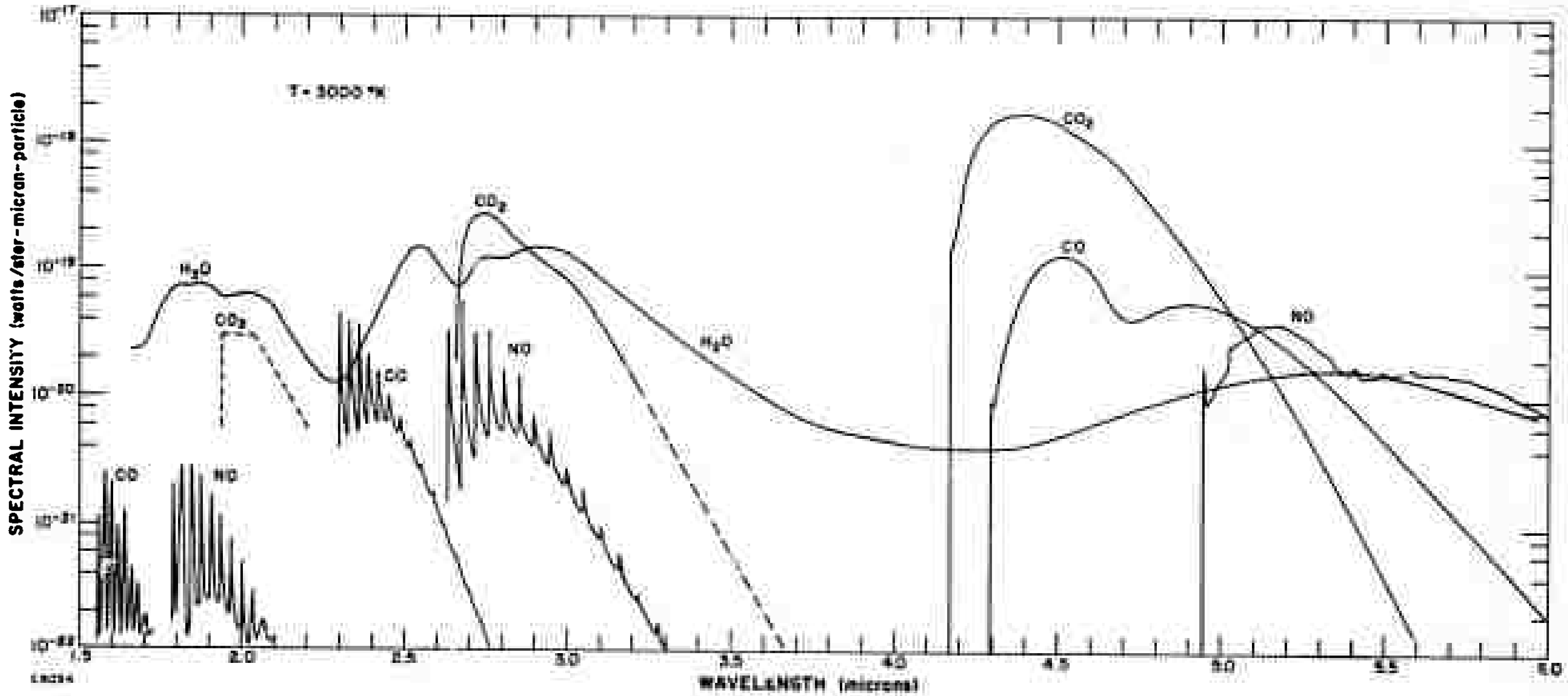

Fig. 7 Theoretical spectral intensity versus wavelength for a number of relevant vibration-rotation bands in the near IR at 3000°K.

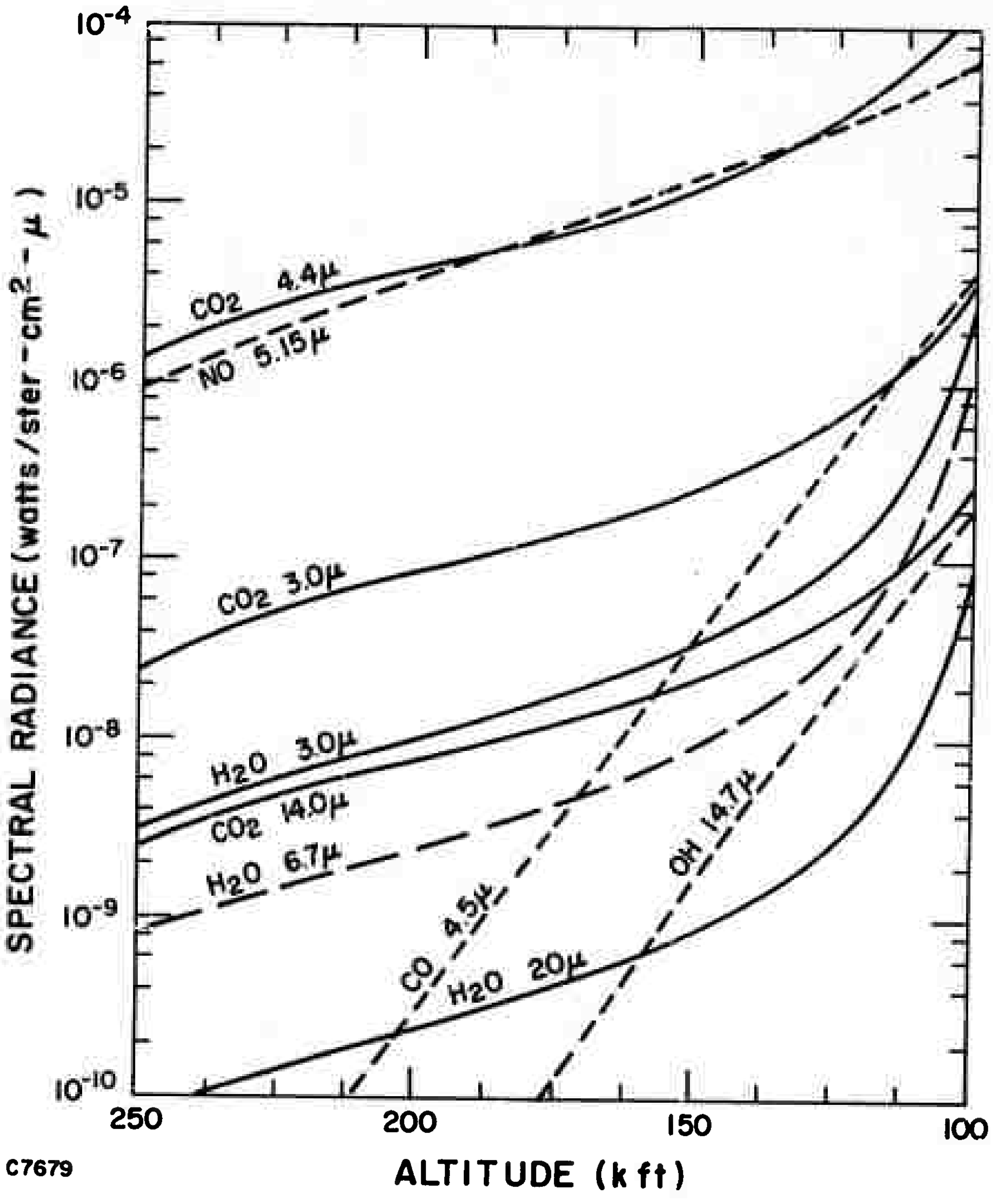

Fig. 8 Boundary layer spectral radiance as a function of altitude predicted for the vehicle shown in Fig. 2. These calculations include both ablation products and ambient carbon dioxide and water.

over the ablation product radiation. Between 150 and 100 kft, however, ablation begins to dominate and the radiation curves increase rapidly. The CO and OH radiation curves, being solely due to ablation products, show the altitude dependence of the ablation product component to the radiation. The radiance plotted in Fig. 8 has the same units as the "earth" spectral radiance shown in Fig. 1 and can be directly compared with that figure; it immediately becomes clear that the boundary layer radiance is small compared to the "earth" except at the lowest altitudes that were considered.

In Fig. 9 we have plotted the spectral radiance of the boundary layer versus wavelength at 100 kft. This figure should be compared directly to the "earth" radiance shown in Fig. 1 where it is seen that the 4.3 μ CO_2 radiation from the boundary layer would dominate that wavelength region while the NO radiation at 5.3 μ could also be relevant. At longer wavelengths the radiation from CO, CO_2, and OH is less than 10^{-6} watts/ster-cm^2-μ and hence would not interfere with seeing the "earth".

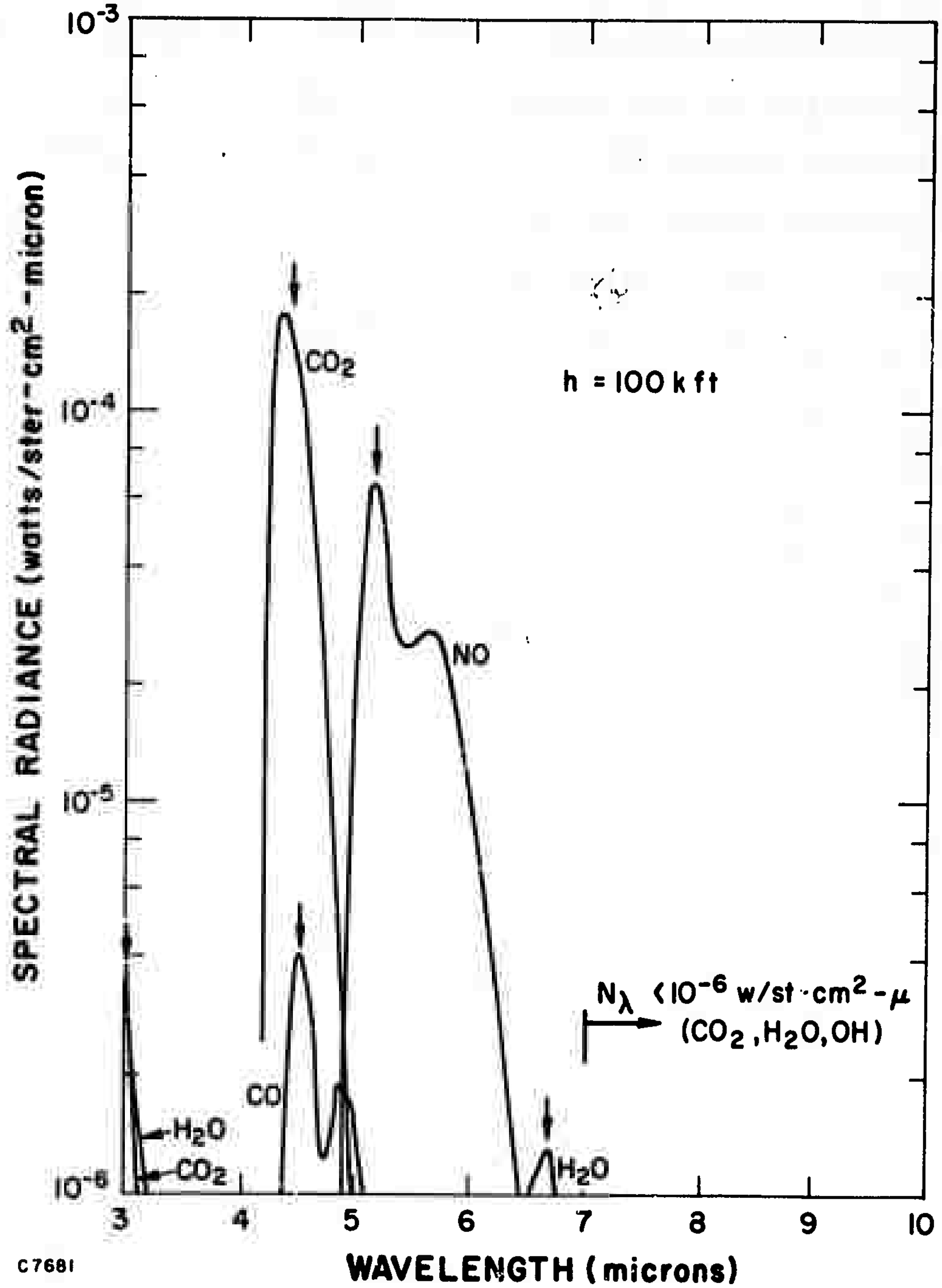

Fig. 9 Boundary layer spectral radiance versus wavelength at an altitude of 100 kft for the vehicle shown in Fig. 2. The tick marks indicate the wavelengths for which intensities were given as a function of altitude in Fig. 8.

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