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AIRBORNE MEASUREMENTS OF SOLAR AND PLANETARY NEAR
ULTRAVIOLET RADIATION DURING THE NASA/ESA CV-900
SPACELAB SIMULATION

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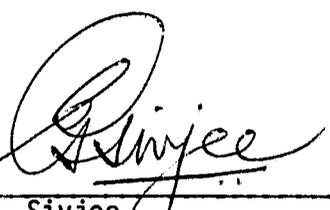
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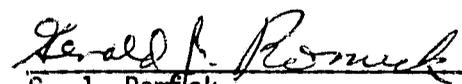
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SUMMARY

Results from a comparative study of the feasibility of employing Experiment Operators on the Space Shuttle to acquire scientifically worthwhile data are presented. The experiments performed during these tests included spectral observations of the Sun and various planets in the near ultra-violet region. The solar measurements have been analyzed in conjunction with data gathered from a previous Shuttle Simulation mission to determine ozone abundance in the terrestrial atmosphere. Using a detailed spectral matching technique to compare airborne solar UV measurements with synthetic spectral profiles of sunlight, we deduce that in winter the total atmospheric ozone abundance is about 0.33 atm-cm at midlatitudes in the northern hemisphere.

INTRODUCTION

In the summer of 1975 the Geophysical Institute of the University of Alaska participated in the NASA/ESA CV-900 Spacelab Simulation Mission with an ultraviolet experiment for spectral observation of the Sun and Venus. In keeping with the goals of the Mission, we trained three Experiment Operators (EOs) to perform our experiments. During the confined period of the Mission the EOs acquired a total of one and a half hours of data from Venus amounting to approximately 350 spectra in the 3050 to 3550 Å wavelength region. The principal investigators repeated these measurements to acquire a data base for comparison with the observations made by the EOs. The results of this comparative study are presented at the end of this report.

One of the more interesting results from the solar UV measurements made during the first (Sivjee, 1976) and second Shuttle Simulation Mission is the determination of ozone (O_3) abundance in the terrestrial atmosphere. A

detailed account of our measurements and the development of a method involving matching of these measurements with spectral solar profiles containing various amounts of O_3 absorption, as well as a critical review of the parameters which enter in Dobson-type O_3 measurements, constitute the bulk of this report.

AIRBORNE ULTRAVIOLET STUDIES OF VENUS

Because of the high atmospheric extinction in the ultraviolet at ground level, an airborne platform offers distinct advantage for planetary optical measurements in the wavelength region below 3500 Å. The joint NASA/ESA Space Shuttle Simulation Program (ASSESS) provided an opportunity to conduct such measurements aboard NASA's Convair 990 jet aircraft, at an altitude of 40,000 feet. The following summary of these measurements is a supplement to the published report on the ASSESS experiments.

The experimental setup for airborne planetary ultraviolet studies consisted of a two-dimensional gyro-stabilized plane mirror (a heliostat) placed near a quartz side window in the aircraft. Objects outside the aircraft could be viewed at elevations between 10° and 40° . A 14" diameter Cassegrain telescope was fitted with an image position analyzed star tracker which fed electrical signals to the movable secondary mirror in the telescope for stabilization of rapid changes in image position and also to the heliostat to compensate for slow changes that were not compensated for by the gyros of the heliostat. Once an object was acquired, this system automatically tracked it within the elevation and azimuth ranges through which the heliostat could be driven to look at an object through the aircraft window.

Our primary objective was to observe Venus in the ultraviolet region.

The telescope image size diameter was 0.5 mm. A quartz lens magnified this to a 5-mm disk in the slit plane of a 1-m Ebert-Fastie spectrophotometer. The primary wavelength region monitored was between 2950 and 3550 Å in the third order, with a resolution of 4 Å. A cooled S20 photomultiplier tube fitted with a quartz window, and operating in pulse counting mode, was used as a detector. A mini-computer, a digital multiplexer, a digital tape recorder and an interactive graphic system permitted data organization for real time analysis and display of the results on a scope and a chart recorder, as well as for magnetic tape recording for subsequent detailed analysis. A D/A converter provided independent records of raw data on both chart and analog magnetic tape recorders. The entire optical and electronic system was adequately automated for single operator control in keeping with the guidelines of the Shuttle Simulation Mission requirements.

Measurements of the solar radiation reflected from Venus were obtained on five flights at elevation angles of 15° - 30°. An hour and a half of data were acquired by the experiment operation during the confined portion of the Mission and two 0.5-h periods were acquired by the principal investigators later in the program. Direct solar and lunar spectra were obtained for the same elevation angles and wavelength resolution during two of the flights. Figure 1a and 1b illustrates typical solar and Venus spectra. Further analysis required normalization of these spectra at one wavelength before obtaining the difference spectrum or ratio spectrum to remove the solar Fraunhofer and terrestrial O₃ absorption features from the Venus spectrum. In a previous set of Venus observations from another expedition using the NASA Convair 990, some absorption features appeared in the wavelength regions of the SO bands. Our current observations, which are

at higher wavelength resolution, can be analyzed to look for conclusive evidence of these bands as well as other features, such as the NH band at 3357 Å which might be present.

AIRBORNE SPECTROSCOPIC MEASUREMENTS OF TOTAL ATMOSPHERIC OZONE

ABSTRACT

An extension of Dobson's method for optical remote sensing of total ozone (O_3) is described. It involves detailed spectral matching of near ultraviolet solar observations with synthetic profiles containing various amounts of ozone absorption. Application of this technique is made to airborne solar measurements in the 3100 to 3600 Å wavelength region. In the 3100 to 3200 Å region, measurements made above the tropopause (around geographic latitude 36.7°N, longitude 121.7°W at ~ 0045 UT on 1/23/74) generally fit synthetic profiles constructed with 0.3 atm-cm of O_3 absorption and Broadfoot's (1972) extra-terrestrial solar irradiance values. However, there are several sections of the solar spectra where the observed intensity is either significantly higher or lower than the calculated value. In addition, several maxima and minima in the observed spectra do not coincide in wavelength with corresponding features in the synthetic profile. Such problems also appear when comparison is made with synthetic profiles based on Arvesen et al's (1969) extra-terrestrial solar irradiance measurements. These discrepancies may arise from a combination of sources, including errors in laboratory measured O_3 absorption coefficients, the extra-terrestrial solar irradiance values and the presence of other UV absorbing species in the stratosphere.

INTRODUCTION

There is growing concern that man-made gaseous pollutants may seriously degrade nature's ultraviolet-shield by depleting existing stratospheric ozone. In this context an obvious question arises: how much ozone is there in the atmosphere above various regions on earth where the output of possibly offensive chemicals, like fluorocarbons, NO etc., differ by orders of magnitude? To date, the most widely used and simple method of routinely remote-sensing O_3 has been optical measurements of sunlight at various wavelengths pioneered by Dobson (1931). Recent advances in spectrophotometric technology have superseded Dobson's prism double monochromator and nulling wedge. However, in almost all cases the new spectrophotometers are operated in the fixed-grating mode and use multiple slits to monitor various wavelengths (Brewer 1973; Heath et al, 1973). Hardware improvement alone does not correct some of the serious problems associated with Dobson's method (Brewer, 1973). Hence, various investigators (e.g. Dobson and Normand, 1957; Brewer and Kerr, 1973; etc.) have experimented with the use of several wavelength-pairs in an attempt to improve the reliability of O_3 measurements. If increasing the number of wavelength-pairs truly refines Dobson-type measurements, it appears obvious that this extension should be carried to its natural limit by scanning the solar spectrum between two widely separated wavelengths at the highest possible resolution. Thus, if solar spectral measurements are made between initial wavelength λ_i and final wavelength λ_f at a resolution $\Delta\lambda$, there will be $m = (\lambda_f - \lambda_i) / \Delta\lambda$ resolution elements and hence $n = m! / (2!(m-2)!)$ independent wavelength pairs. Instead of calculating intensity-ratios for this formidable array of wavelength-pairs to determine

the total amount of terrestrial atmospheric ozone, another approach is to construct synthetic solar spectral profiles appropriate for different amounts of ozone absorption including correction for Rayleigh scattering, and numerically compare the measured and calculated intensities at each sampling point of the solar spectrum. This approach has a two-fold advantage; not only does it vastly increase the number of wavelength-pairs used in determining O_3 abundance but it also provides an opportunity to match the wavelength scales of the observed and synthetic solar profiles. The need for exact wavelength coincidence stems from the presence of myriads of Fraunhofer absorption features in the solar spectra. Consequently, even a small wavelength mismatch between ground-based or airborne solar measurements and extra-terrestrial solar irradiance values can lead to a large disparity in the intensity ratios and hence in the determination of O_3 abundance.

In practice, the number of independent wavelength pairs available from a continuous scan of the solar spectrum is limited by the constraint of operating at the same resolution as the extra-terrestrial solar irradiance measurements and O_3 absorption coefficients which are used in reducing the observations. The most reliable values of these two parameters, presently available, were derived from spectrophotometric measurements made at about 3A resolution. Thus, in this analysis our solar UV measurements made at about 3A resolution were used for comparison with the synthetic spectral profiles. In the 3100 to 3200 A region there is, on the average, a good fit between our observations made above the tropopause (around geographic latitude $36.7^\circ N$, longitude $121.7^\circ W$ at ~ 0045 UT on 1/24/74) and the synthetic solar spectral profiles constructed with 0.3 atm-cm of O_3 . However, for the wavelength intervals 3165 to 3176 A and 3186 to 3195 A the observed intensities

are smaller than the calculated values. Some disparity in the wavelengths of corresponding features in the observed and synthetic solar profiles as well as in the amount of structure in the two spectra are also evident. Similar problems arise when comparing our solar observations in the 3100 to 3600 Å region with synthetic solar profiles based on presently available extra-terrestrial solar irradiance values in this wavelength region. Some of these problems may be indicative of errors in the O_3 absorption coefficients and in the extra-terrestrial solar irradiance values and wavelengths. Others may arise from absorption of solar UV by stratospheric minor constituents such as SO , SO_2 , HCl , ClO , NO , NH , NH_3 etc.

MEASUREMENTS

For the purpose of determining O_3 abundance we have employed two sets of solar near-UV measurements made on board NASA's Convair 990 jet aircraft at altitudes near 40,000 feet. Both sets of spectra, monitored on January 23 and 24, 1974 came from a well-baffled half meter Ebert spectrophotometer operating in analog mode at various resolutions between 0.3 and 7 Å. Quartz optics were employed throughout the optical path length. Two typical solar spectra, monitored with the spectrometer scanning between 3050 and 3600 Å in the first order at a resolution of 0.4 Å and 7 Å respectively, are displayed in Fig. 2. These measurements were made near geographic latitude $36.7^\circ N$, longitude $121.7^\circ W$ when the sun was about 5° above the horizon.

Additional airborne solar measurements were taken in May and June, 1975 during the joint NASA/ESA Space Shuttle Simulation Mission. This time, a

one-meter Ebert spectrophotometer operating in photon-counting mode was coupled to an automatic tracking system (Sivjee and Romick, 1976). The operating system provided for real-time manipulation of the data, including cross-correlation, normalization and point by point subtraction of any two spectra. Results from this series of measurements are similar to those obtained during the January observing period so are not included here.

ANALYSIS

Solar electromagnetic radiation, replete with Fraunhofer absorption features, acquires telluric absorption features in passing through the earth's atmosphere. In the near-ultraviolet region the absorption is due mostly to O_3 though other species such as SO, SO_2 , ClO, NH, NH_3 , NO etc. may also contribute to absorption. Additionally, the spectral distribution of sunlight is modified by Rayleigh and aerosol scattering. Consequently, the intensity I (in photons/cm²-sec-A) of sunlight at wavelength λ , detected by a spectrophotometer at a height h above the earth's surface when pointing at the sun along zenith angle θ , is related to the extra-terrestrial solar irradiance I_0 by Beer's law.

$$I(\lambda, h, \theta) = I_0(\lambda)S(\lambda)\exp[-K(\lambda)\mu(h)x_1(\theta) - \tau(\lambda, h)x_2(\theta) - \delta(\lambda, h, \theta)] \quad (1)$$

Here $S(\lambda)$ = spectral sensitivity of the spectrophotometer,

$K(\lambda)$ = ozone absorption coefficient (in cm⁻¹) under STP condition,

$\mu(h)$ = total ozone content (in atm-cm) along the zenith above height h km,

$x_1(\theta)$ = path length through ozone at zenith angle θ relative to that in the vertical direction,

$\tau(\lambda, h)$ = Rayleigh optical thickness, in the zenith, from h km above earth's surface to ∞ ,

$x_2(\theta)$ = path length through air at zenith angle θ relative to the vertical direction,

$\delta(\lambda, h, \theta)$ = optical thickness of aerosols and other absorbing and scattering species in air along the look direction.

If all the parameters in equation (1) are precisely known, the calculated values of $I(\lambda, h, \theta)$ should correspond exactly to observed values. Conversely, if all the parameters except $\mu(h)$ are known then the $I(\lambda, h, \theta)$ can be calculated for different values of $\mu(h)$ and compared with the observed $I(\lambda, h, \theta)$ until the two agree. The latter is the basis of optical remote sensing of O_3 . The precision of this method is limited by the accuracy of our knowledge of various parameters which enter into the calculations. We will examine each parameter separately to determine its impact on the accuracy of ozone measurements.

a) Spectral sensitivity of the spectrophotometer

Absolute calibration of the Ebert spectrophotometers employed in our solar measurements were performed using a standard quartz-iodide lamp and a Lambert surface (Sivjee, 1970; Rees et al, 1976). The combined uncertainty in the relative brightness of the lamp and the signal-to-noise ratio of the spectrophotometer's output does not exceed 5%.

b) Extra-terrestrial solar irradiance

There is a very critical lack of reliable measurements of $I_0(\lambda)$ in the near-ultraviolet region at moderate resolution. Discounting ground-based photographic measurements, there are only two photometric measurements of extra-terrestrial solar irradiance at resolution better than 5 Å in the region between 3000 and 3600 Å. Broadfoot's (1972) rocket measurement at 250 km constitute the most direct observation of the solar near-ultraviolet presently available below 3200 Å at 3Å resolution; the overall error in these

measurements is quoted at $\pm 10\%$. Arvesen et al (1969) made airborne solar measurements covering a very large wavelength range with a continuously calibrated spectrophotometer. They extrapolated the solar irradiance values to zero air-mass through Langley plots at selected wavelengths. The reported error in these measurements is less than 8% in the near-UV. These observations present two main problems when employed in equation (1). Firstly, while the measurements were made at 3 Å resolutions the solar irradiance values are quoted at 4 Å intervals. In practice, it takes about five samples per resolution element to preserve the spectral integrity of measurements. Hence, Arvesen et al's (1969) solar measurements cannot be used for analysis of Dobson-type measurements made at 3 Å resolution. This point will be illustrated later. Secondly, correction for atmospheric transmittance was carried out at selected wavelengths, with a smooth curve fit to these measurements to determine the transmittance at all wavelengths. Whether this technique adequately corrects for the structure in ozone absorption is unclear.

Overall, the lack of accurate high resolution solar extra-terrestrial irradiance data may be one of the more significant factors affecting optical remote sensing of O_3 .

c) O_3 absorption coefficients

Hudson (1971) has reviewed currently available O_3 absorption coefficients. He notes that the difference between Grigg's (1968) and Inn's and Tanaka's (1952) values is within their quoted cross-section errors ($\pm 10\%$). However, differences as large as 5 Å, which is greater than the quoted wavelength errors, have been pointed out by Griggs (1968) in the location of maxima and

and minima in absorption. No tables of numerical values of the absorption coefficients are available and reading the numbers from small scale published graphs introduces errors in wavelength and coefficient values that are larger than the measurement errors.

According to Griggs (1968), the O_3 absorption coefficients of Inn and Tanaka (1953) in the Huggin's band are preferred to those of Vigroux (1953). Whether there is a difference in coefficient values or in the wavelengths of maxima and minima in the Huggins band is not mentioned. On the other hand, coefficient values measured by Hearn (1961) show less than a 5% difference with Vigroux's measurements in the 3000 to 3500 A region.

There appears to be no documented case of any large difference in the various laboratory measured values of ozone absorption coefficients in the Huggins band. In this region all three of the extensive measurements (i.e. by Vigroux (1952), Inn and Tanaka (1953) and Griggs (1968)) seem to give values within the experimental errors. (There is, however, a large difference in the Hartley band region (Hearn (1961))). We have settled on Vigroux's (1952) measurements, mostly because of the availability of numerical values in tabular form compiled by R. P. Gast (Elterman and Toolin, 1965).

While the expected error in O_3 absorption coefficients may be about 10%, it is difficult to estimate the possible errors in wavelength and their impact on Dobson-type O_3 measurements.

d) Rayleigh optical thickness

Only calculated values of the Rayleigh optical thickness are available (Elterman and Toolin, 1965). The error in relative values at any two wavelengths in the near-UV may be less than 1%.

e) Path lengths through ozone and air at different solar zenith angles

For measurements made at solar zenith angles $0^\circ < \theta < 70^\circ$, x_1 and x_2 in equation (1) can be set equal to $\sec\theta$. This approximation significantly overestimates x_1 and x_2 for $\theta > 70^\circ$. Since our airborne measurements at 12 km altitudes were made at $\theta \approx 85^\circ$, we have numerically calculated x_1 and x_2 using an average O_3 height profile (Elterman and Toolin, 1965) and a model atmosphere appropriate for the location and time of measurements (U. S. Standard Atmosphere Supplements, 1966). The results are displayed in Fig. 3 in the form of relative path length, with respect to the vertical, versus zenith angle.

f) Absorption and scattering by minor atmospheric constituents other than O_3

Most of the Dobson-type ground-based measurements are made on clear days to avoid problems associated with water absorption and scattering by aerosols. Our airborne observations, made above the tropopause, should be free of this particular problem. However, stratospheric minor constituents such as SO , SO_2 , HCl , ClO , NO , NH , NH_3 , etc. can contribute to absorption of solar UV at some wavelengths in the 3100 to 3600 Å region, effectively giving rise to higher O_3 values. In the absence of accurate abundance values and height profiles of these species, it is not feasible to include their contribution to the synthetic profile calculations. The calculated profiles contain only O_3 absorption, corrections for Rayleigh scattering and relative sensitivity of our instruments. Hence, some of the differences between the measured and the calculated solar intensities may be indicative of absorption by other minor constituents of the stratosphere.

Excluding the problem discussed in section f) above, the cumulative error in O_3 measurements, arising from the reported uncertainties in the

parameters in equation (1), is probably less than 25%. This value does not include errors arising from basic spectral differences between I and I_0 . As shown in Fig. 2 and also clearly illustrated by Wilson et al (1953), the measured ratio of both $I(\lambda)$ and $I_0(\lambda)$ at any two wavelengths depends critically on the resolution of the spectrophotometer employed because of the highly structured solar spectrum. The effect of ozone absorption on UV light is more clearly illustrated by approximating the solar spectrum by a black body curve ($T=5500^\circ\text{K}$ between 3000 and 3600 Å, (Gast, 1960)), which is devoid of the complicating Fraunhofer features. Figure 4 demonstrates the impact of 0.3 atm-cm of O_3 absorption on the blackbody radiation as it penetrates the atmosphere in the vertical direction, at 45° and 85° zenith angles; correction for Rayleigh scattering has been applied. According to Fig. 3, most of the structure in the UV spectrum observable from ground-based or airborne measurements is confined below 3400 Å. The effect of O_3 absorption increases at short wavelengths up to a cut-off wavelength which depends on solar zenith angle. Clearly, the most fruitful region to analyze our measurements, made at $\theta=85^\circ$, is between 3100 and 3400 Å. Unfortunately, the most accurate measurements of extra-terrestrial solar irradiance are available only at wavelengths below 3200 Å. Consequently, we have concentrated on the analysis of our measurements $I(\lambda)$, made between 3050 and 3199 Å, using Broadfoot's (1972) $I_0(\lambda)$ values. However, we have also included the analysis of the entire wavelength range scanned during the airborne measurements using Arvesen et al.'s (1969) I_0 values.

Figure 5 (upper curve) shows the extra-terrestrial solar spectrum of Broadfoot (1972) modified by the spectral response of our half-meter Ebert spectrophotometer. The absorption effect of 0.1, 0.2 and 0.3 atm-cm of O_3 and the effect of Rayleigh scattering on this radiation at solar zenith

angle 85° , as it penetrates to airplane altitude (12 km), is illustrated in the lower three curves of Fig. 5. Absorption by O_3 is seen to alter the solar spectrum drastically. Figure 6 shows our solar observation at about 2 Å resolution made at an altitude of 12 km near geographic latitude $36.63^\circ N$, longitude, $121.62^\circ W$ on January 24, 1974 at UT 0045 when the sun was 5.71° above the horizon. Synthetic solar profiles based on Broadfoot's extra-terrestrial solar irradiance values at 3 Å resolution appropriate for 0.3 and 0.35 atm-cm of O_3 , in the vertical above altitude 12 km, are also displayed in the same diagram. A slightly higher-resolution measurement was chosen for comparison with synthetic profiles based on relatively lower-resolution extra-terrestrial irradiance values to illustrate differences in the structure of the two spectra. We have applied a sliding-average filter to the measurements shown in Fig. 5 to reduce them to 3 Å resolution for comparison with the synthetic profiles. In general, our observations fit synthetic profiles with 0.3 atm-cm of O_3 , though some significant differences are apparent.

Our airborne measurements of direct sunlight from 3050 to 3600 Å at 3.5 Å resolution are displayed in Fig. 6. This spectrum was monitored on January 23, 1974 at UT 0058:30 when the sun was 3.54° above the horizon. At this time the airplane was flying at an altitude of 12 km near geographic latitude $37.81^\circ N$, longitude $122.73^\circ W$. Synthetic solar spectral profiles based on Arvesen et al's (1969) extra-terrestrial solar irradiance values for 0.1, 0.2 and 0.3 atm-cm of O_3 , are shown in Fig. 7. The closest match between observed and synthetic profiles appear to occur for 0.2 atm-cm of O_3 , but large differences are apparent. All of our other solar UV measurements yield similar results when compared with these synthetic profiles.

DISCUSSION

As shown in Fig. 6, airborne solar observations below 3164 Å and between 3176 and 3180 Å as well as between 3189 and 3192 Å seem to fit synthetic profiles constructed with Broadfoot's (1972) measurements of extra-terrestrial solar irradiance and 0.3 atm-cm of O₃ absorption. In the wavelength region 3165 - 3176 Å and above 3186 Å our observations imply greater than 0.3 atm-cm of O₃ absorption if the laboratory measured O₃ absorption cross-sections are correct and absorption by other stratospheric minor constituents is ignored. This discrepancy in O₃ abundance implied by different sections of a small (~ 100 Å) wavelength region cannot be attributed to changes in atmospheric sampling regions, since the same results were obtained from all consecutive scans (the aircraft position changed by ~ 3 km during an individual scan period).

Four explanations can be advanced for the differences between the observed and the synthetic solar spectra. First, perhaps the spectrophotometer's responsivity varied drastically over small wavelength regions. We recalibrated the instruments several times before, during and after the flights and detected no such variations. Secondly, the extra-terrestrial irradiance values may be too low in the wavelength regions where the measurements imply greater than 0.3 atm-cm of O₃ absorption. Since Broadfoot's (1972) measurements were made with an instrument very similar to ours, and it has been established by Broadfoot (1972) that there were no large detailed structures in the instrument's responsivity over very small (~ 10 Å) wavelength sections, this second possible source of error seems ruled out also. Thirdly, perhaps the O₃ absorption coefficients in the wavelength region 3165 - 3176 Å and above 3186 Å are too small. An increase of less

than 10% in the O_3 absorption coefficients around 3165 - 3176 Å and 3186 - 3190 Å would suffice to match the observed and synthetic solar spectra profile for 0.3 atm-cm of O_3 , in these regions. However, above 3195 Å a much larger increase in O_3 absorption coefficients would be required. Fourthly, there may be minor constituents in the stratosphere which absorb solar UV around these wavelengths. According to Pearce and Gaydon (1950), SO, CH_2O , CS and NO absorb at these wavelengths. Some of the bands of SO_2 (Thompson et al., 1963), ClO (Nicols, 1976), NO_2 and N_2O_4 (Hall and Blacket, 1952) also fall in these wavelength regions.

It was pointed out earlier that in Fig. 6 our measurements made at 2 Å resolution are compared with synthetic profiles based on coarser extra-terrestrial solar irradiance values. We have applied a sliding average digital filter technique to degrade our measurements to 3 Å resolution and compared the results with the synthetic profiles shown in Fig. 5. The effect of this filtering was a slight broadening of the peaks and valleys without significantly affecting the relative intensities or the details of the spectrum. Hence, the observed differences between our measurements and the synthetic profiles are not due to differences in resolution. However, between 3145 and 3155 Å the coarser resolution synthetic profiles of the solar spectrum are more structured than the finer resolution observed profiles. We can only attribute this difference to errors in the maximum and minimum values of the O_3 absorption coefficients in this wavelength region. On the other hand, our measurements, even when degraded to effective resolution of 3 Å, still show a minimum at 3143.5 Å, a maximum around 3176.5 Å and an inflection around 3186 Å, all of which are missing from the synthetic profiles.

These differences could be the results of errors in O_3 absorption coefficients or due to other species absorbing near these wavelengths. Lastly, a slight wavelength mismatch (~ 1.5 A) is apparent between the observed minimum at 3168.5 A and the minimum in the synthetic profiles at 3170 A: this difference cannot be attributed to wavelength error in either our instrument or in Broadfoot's. His instrument was subjected to extensive wavelength checks and cross-calibrations with very detailed high-resolution solar spectra, and we have fitted our observations to all the major peaks and valleys in these spectra.

Airborne solar UV measurements shown in Fig. 7 were made around the same time and about the same location as those shown in Fig. 6. Yet, the synthetic solar spectra, constructed with Arvesen et al.'s (1969) extra-terrestrial solar irradiance values, when compared with our observations, yield about 0.2 rather than 0.3 atm-cm of O_3 . The problem here results mostly from a mismatch in the spectral resolution of the two measurements. As pointed out earlier, even though Arvesen et al.'s (1969) measurements were made at 3 A resolution, their tabulation of the results at 4 A intervals effectively smeared these values to a resolution of perhaps 10 - 15 A. This smearing effectively reduced the relative intensities of the peaks and valleys in the synthetic spectra. (See for example Fig. 1 and Wilson et al, 1953). Additionally, the atmospheric transmittance determination of Arvensen et al. (1969) may not have been detailed enough, in wavelength, to correct for all of the O_3 absorption. Absorption by NH (Brewer, 1972; Nicols, 1972) and ClO (Nicols, 1975) as well as SO (Pearce and Gaydon, 1950), SO_2 , NO , NH and CH (Thompson et al, 19630, NO_2 and N_2O_4 (Hall and Blacet, 1952) would also contribute to the differences between the

airborne observations and the synthetic spectra shown in Fig. 6.

Many studies have shown variations in O_3 abundance of up to 10% (Komhyr et al., 1973; Christie, 1973). Since changes in O_3 by these amounts are of concern in questions of human response to BUV radiation, substantiating the validity of the variations is of some importance. Although most studies have been very carefully done, the possibility of anomalous O_3 values arising from solar UV absorption by other stratospheric constituents can not be completely ruled out, especially when using the Dobson-type fixed wavelength method of total O_3 determination.

CONCLUSION

Ground-based or airborne observations of solar near-UV radiation can be analyzed to determine total O_3 in the atmosphere provided the following precautions are taken:

- (1) An exact match in the wavelengths of the measurements with reliable photometric observations of extra-terrestrial solar irradiance is assured;
- (2) the spectral resolutions of the two measurements are the same;
- (3) the choice of wavelengths is judiciously made to avoid regions where possible errors in O_3 absorption coefficients and the presence of absorption by other species occurs;
- (4) a large number of O_3 determinations are made from the intensity ratios at various wavelength pairs and only values showing a small dispersion from the mean are used in determining the average O_3 abundance.

These conditions are more easily met in the spectral matching technique which provides a detailed check on the wavelength coincidence and resolution of extra-terrestrial solar irradiance and ground-based or airborne observations of sunlight. This method clearly distinguishes wavelength regions that show

anomalous O_3 abundance values due to errors in O_3 absorption coefficients, contamination by other stratospheric minor constituents and uncertainties in other parameters in equation (1).

Errors in O_3 absorption coefficients and in the wavelengths of their maxima and minima as well as the presence of other UV absorbing species give rise to significant differences in O_3 abundances at wavelengths between 3165 and 3199 Å. A similar analysis between 3200 and 3600 Å shows that the lack of accurate extra-terrestrial irradiance values at moderate resolution and the possible absorption of solar UV by other stratospheric constituents may be the dominant source of errors for O_3 determination.

Using airborne spectral photometric measurements the O_3 abundance above 12 km altitude near geographic latitude 36.7°N, 121.7°W at UT 0045 on January 23, 1974 was determined to be 0.3 atm-cm along the vertical direction. This translates to 0.33 atm-cm of total ozone above sea-level.

Hopefully, during the Space Shuttle era extensive direct measurements of solar extra-terrestrial irradiance will become available. Coupled with more refined O_3 absorption coefficient measurements, they should greatly improve the accuracy of optical remote sensing of O_3 .

Feasibility of employing an EO to operate several experiments on the Space Shuttle

Extensive quality assurance and detailed documentation of experiments during the Apollo era made space science measurements very costly. One way of reducing the cost of space science experiments during the Shuttle era is to transfer the total responsibility for individual experiment hardware performance on-board the Shuttle to the principal investigators,

and deflate the paperwork on operational procedure by assigning scientists as Experiment Operators (EO) to conduct the experiments. The success of the latter depends immeasurably on the training provided to the EOs to familiarize them not only with routine hardware operation but also the scientific objectives and approach taken to achieve them. If an EO is to effectively replace the investigator he must at least partially share the enthusiasm and commitment of the investigator to the experiment and be familiar enough with the experiment to make decisions on the basis of the results from real time assessment of the measurements without continuous contact and instructions from the other investigators during a shuttle flight.

A test for the EO approach to shuttle experiments was provided during the NASA/ESA CV-990 Space-lab Simulation Mission in May and June of 1975. One principal EO and two secondary EOs were assigned to the ultraviolet experiment described in this report. However, in addition to this experiment all three EOs were also responsible for simultaneous operation of various other experiments.

Because of budgetary constraints, the extensive training plan submitted by the investigators could not be executed in its entirety. Similarly, complete experiment assembly had to wait for actual installation within the aircraft. While the primary EO was knowledgeable about the optical instruments, the digital data processing system employed for real-time analysis and the tracking system required more familiarity than was possible to impart to the EO in the allotted time. Consequently, to substitute for this basic understanding the primary EO insisted on very detailed written instructions for the operation of every part of the experimental system.

This requirement tended to negate the main objective of the Mission in terms of proliferation of paperwork. In addition, the time scale and budget limitations placed undue stress on the investigators who had not originally planned for such an extensive task.

The primary objective of the ultraviolet experiment was spectroscopic observation of Venus. During the confined period, Venus was observable from the airplane for approximately 5 hours. The EOs acquired about one and one-half hours of measurements partly because the telescope used for observing Venus was shared with another experiment. However, some time was lost because of EO error, tracking system target acquisition difficulties and lack of complete familiarity with the tracking system.

One equipment problem developed during the confined period. Working with instructions from the ground-based engineer, relayed through the audio and video channels, the principal EO performed an admirable job in correcting the problem. However, due to the variety of tasks on-board and some lack of personnel involvement with the experiments there was no real time assessment of the data by the EOs; the EOs did not attempt to change equipment configuration or mode of operation to improve the quality of the data based on assessment of real-time output. Following the EO flights, the principal investigators modified the optical focussing system to improve the signal to noise ratio of the spectrophotometer when observing Venus. Whether this could have been done by the EO if miscellaneous equipment was available is unknown. However, such ingenuity may spell the success or failures of a particular Shuttle Mission experiment.

On the whole the EOs did a good job. The quality of the data would have improved if the EOs had been more intimately involved with the scientific experiment. However, this requires a long training period and a genuine

sharing of the scientific goals of the experiment. The EO should truly be a co-investigator who participates in the formulation of the scientific objectives, experimental set-up and operational decisions. Otherwise, he will be under the stress of performing a job for somebody else with the resultant fear of being held accountable for all errors. The latter situation tends to force the EO to merely follow the operating instructions given to him by the principal investigators, performing tasks by the numbers in a fixed time schedule.

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FIGURE CAPTIONS

- Fig. 1 Solar and Venus ultraviolet spectra between 2970 and 3540 Å at 4Å resolution.
- Fig. 2 Solar near UV spectra at 0.4 Å (lower curve) and 7 Å (upper curve) resolution.
- Fig. 3 Path length through ozone and air, relative to the vertical, at different zenith angles.
- Fig. 4 Black-body radiation curves outside the atmosphere (top curve) and at 12 km altitude along zenith, at 45° and 85° zenith angles. The latter three curves are normalized at 3600Å.
- Fig. 5 Extra-terrestrial solar spectrum of Broadfoot modified by spectral response of our spectrometer (upper curve). Absorption effect of 0.1, 0.2 and 0.3 atm - cm of O₃, as well as Rayleigh scattering, in this radiation at solar zenith angle 85°, as it penetrates to airplane altitude (12 km) is shown in the lower three curves.
- Fig. 6 Airborne solar observations between 3100 and 3200 Å (solid curve) and synthetic solar spectral profiles for 0.3 and 0.35 atm - cm of O₃ (dashed curves). The curves are normalized at 3190Å.
- Fig. 7 Airborne solar observations between 3050 and 3600 Å (solid curve) and synthetic solar spectral profiles for 0.1, 0.2 and 0.3 atm - cm of O₃ (dashed curves).

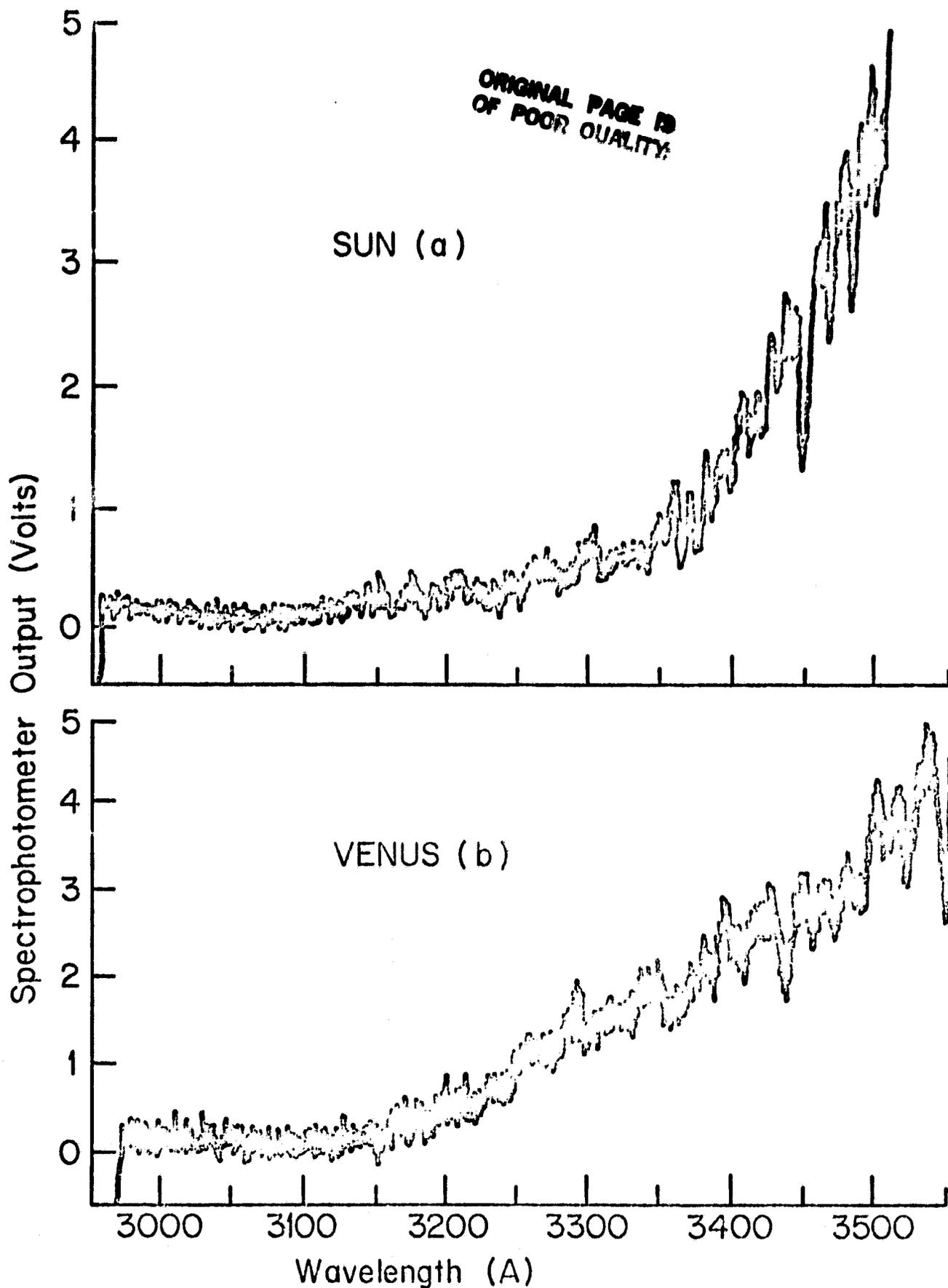


Fig. 1 Solar and Venus ultraviolet spectra between 2970 and 3540 Å at 4Å resolution.

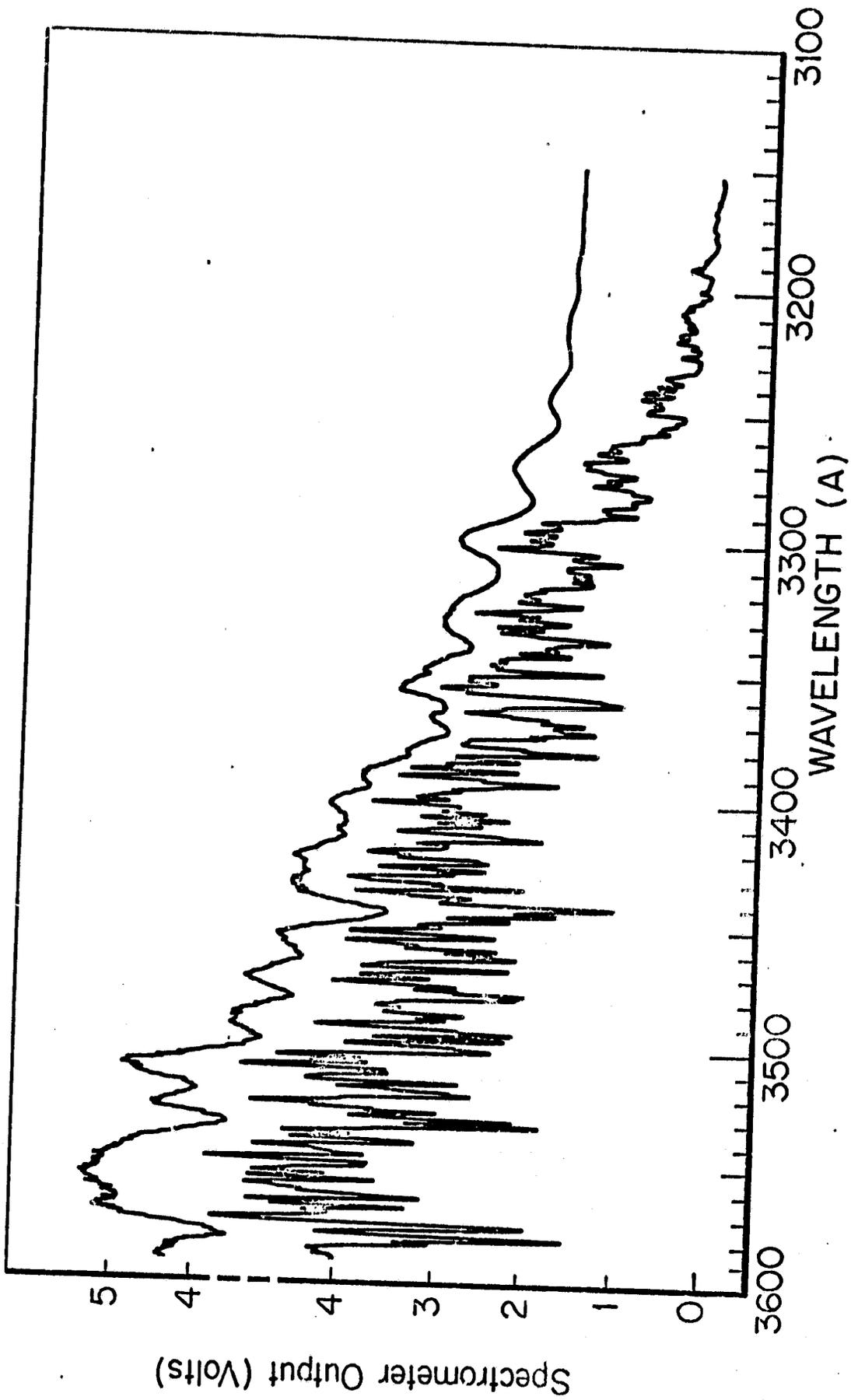


Fig. 2 Solar near UV spectra at 0.4 Å (lower curve) and 7 Å (upper curve) resolution.

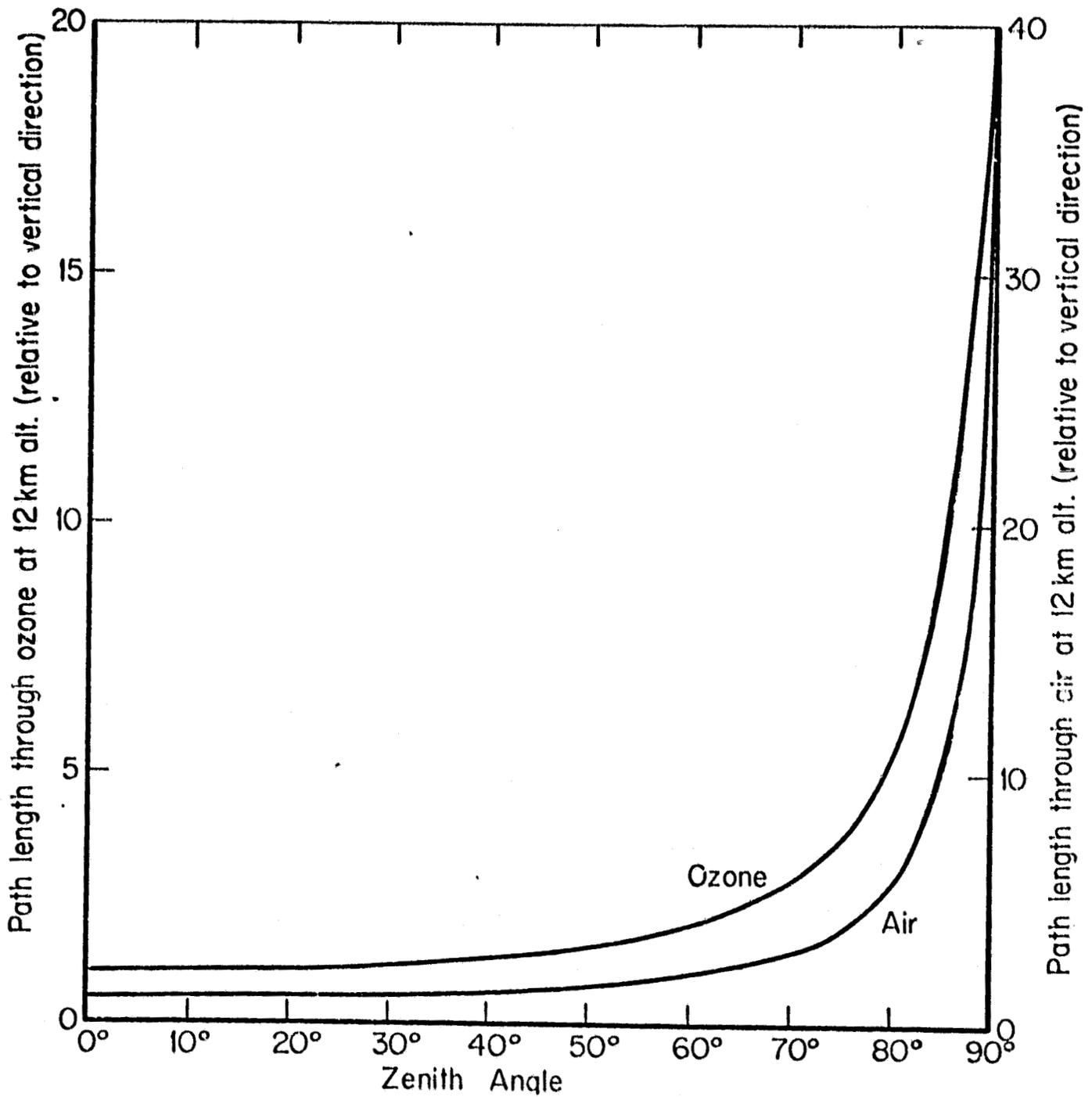


Fig. 3 Path length through ozone and air, relative to the vertical, at different zenith angles.

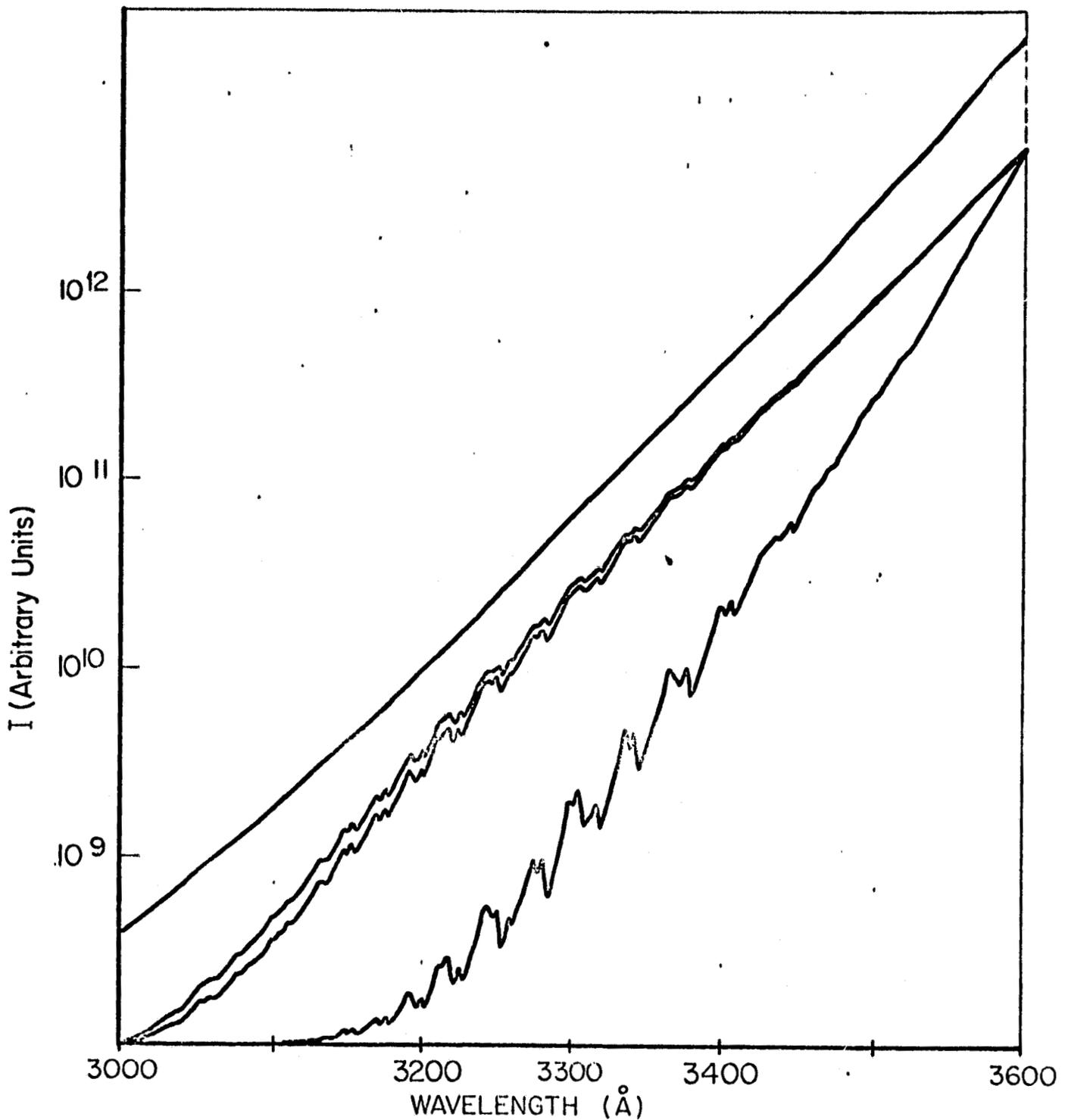


Fig. 4 Black-body radiation curves outside the atmosphere (top curve) and at 12 km altitude along zenith, at 45° and 85° zenith angles. The latter three curves are normalized at 3600Å.

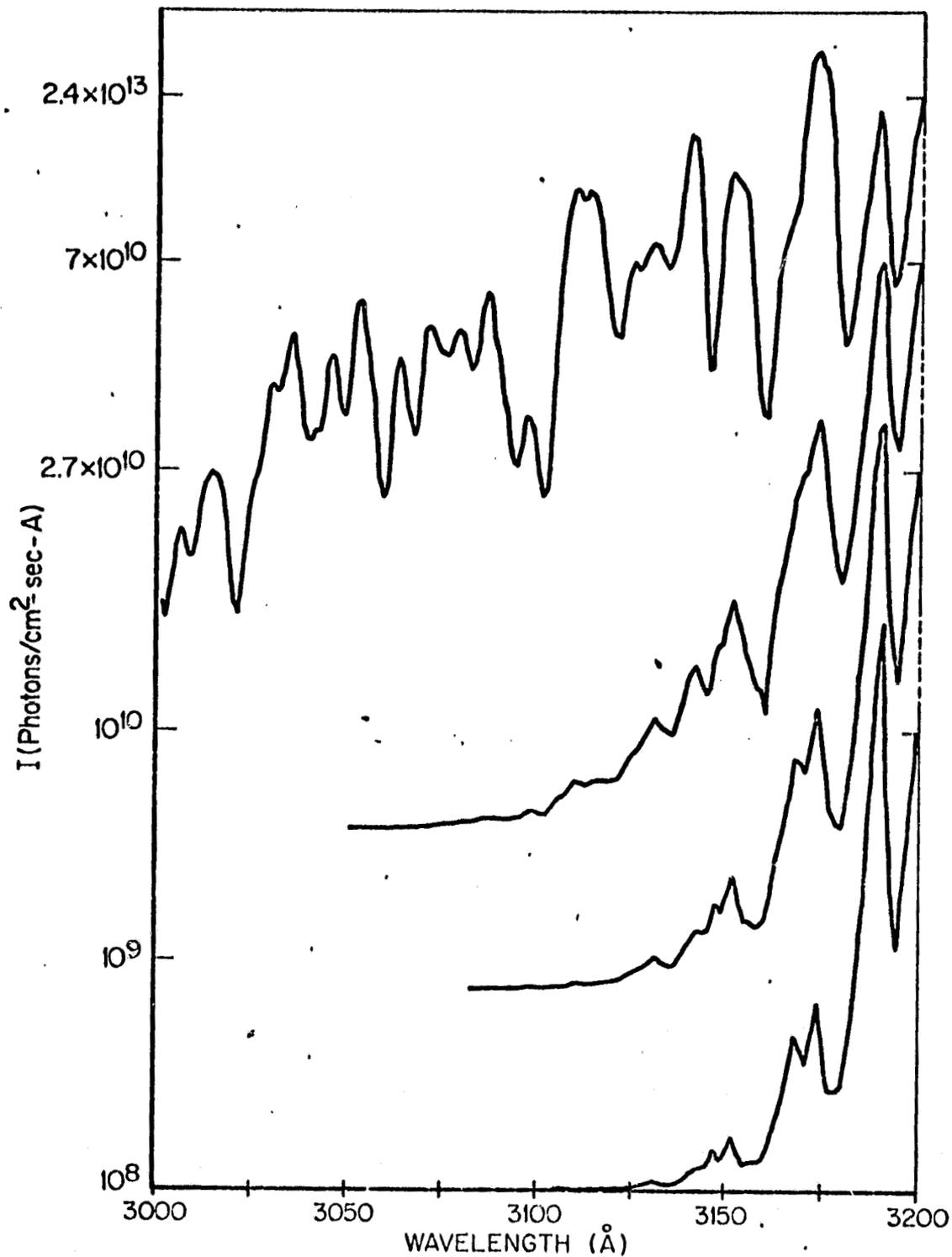


Fig. 5 Extra-terrestrial solar spectrum of Broadfoot modified by spectral response of our spectrometer (upper curve). Absorption effect of 0.1, 0.2 and 0.3 atm - cm of O_3 , as well as Rayleigh scattering, in this radiation at solar zenith angle 85° , as it penetrates to airplane altitude (12 km) is shown in the lower three curves.

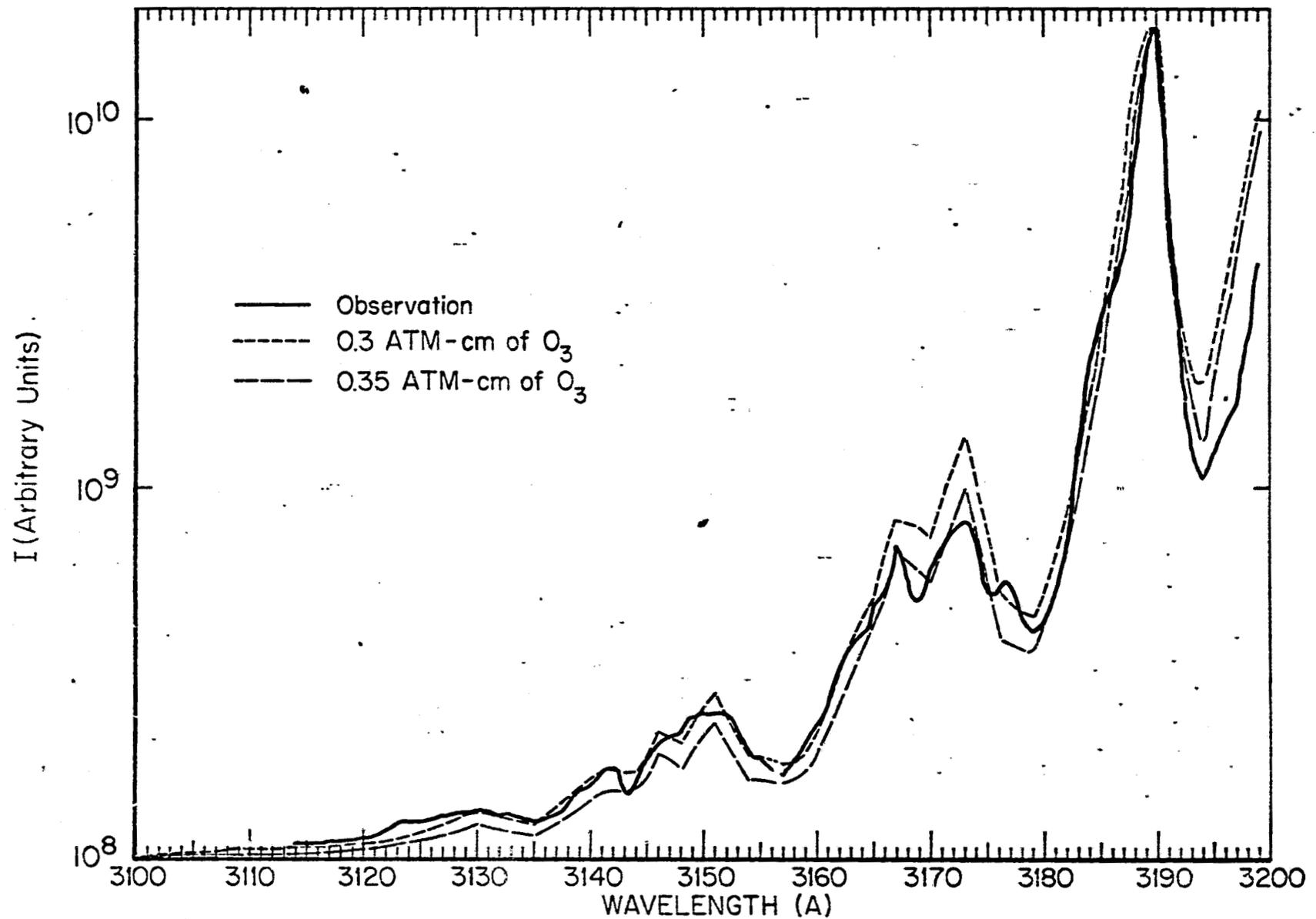


Fig. 6 Airborne solar observations between 3100 and 3200 A (solid curve) and synthetic solar spectral profiles for 0.3 and 0.35 atm - cm of O_3 (dashed curves). The curves are normalized at 3190A.

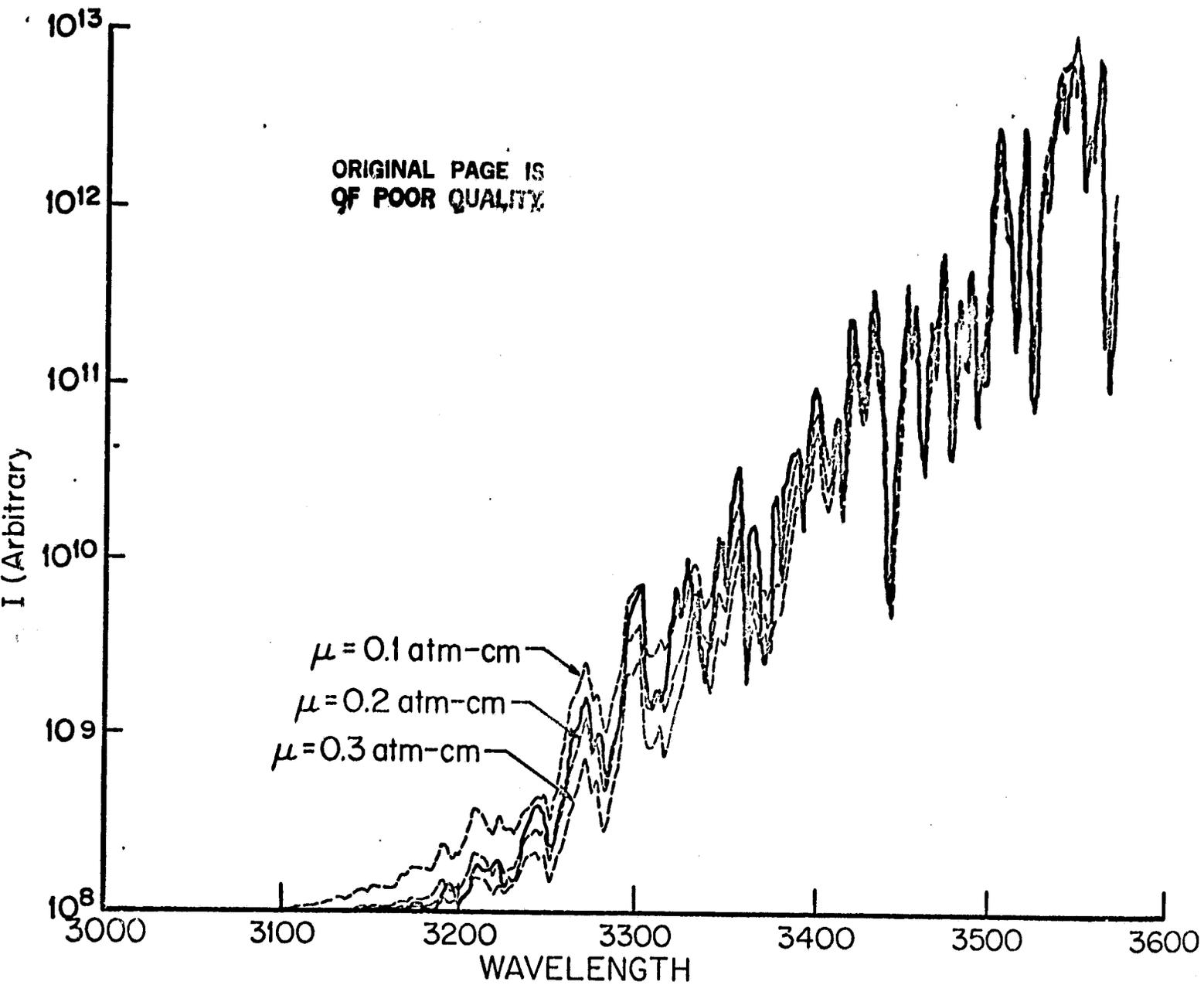


Fig. 7 Airborne solar observations between 3050 and 3600 A (solid curve) and synthetic solar spectral profiles for 0.1, 0.2 and 0.3 atm - cm of O_3 (dashed curves).