FINAL REPORT

on

A ROCKET EXPERIMENT TO MEASURE THE EXTREME ULTRAVIOLET DAYGLOW

(Javelin Rocket Flight 8.40)

Grant No. NSR-05-018-067

Submitted by
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I. INTRODUCTION

The present report summarizes the results of the Javelin 8.40 research program. The unreported work from June 1 through the contract termination on October 31, 1967 is also included in this second and final report. The rocket experiment developed during the contract period was not flown until April 10, 1968 and it seemed desirable to postpone this final report until the flight results could be included. The data have now been analyzed and the results are presented in the scientific discussion. It should be emphasized, however, that the analysis of the data obtained below 300km. is somewhat uncertain. Further model calculations with emphasis on particle excitation cross sections and various reaction rates are required.

The details of the flight instrument are discussed in Section II. Section III contains the flight data analysis. This portion of the report will be submitted for publication to the Journal of Geophysical Research. The results are found to agree surprisingly well with radiative transfer theory. In addition, the shape of the altitude dependence of the dayglow agrees very well with that obtained on the same flight by Professor Donahue[I] who used a completely different method

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[I] Prof. T. Donahue, University of Pittsburgh, Private communication, April (1969).

of detection. His absolute intensity, however, is a factor of two greater than the present value.

II. THE FLIGHT INSTRUMENT

In recent years, rocket measurements of extreme ultraviolet (XUV) radiation in the airglow have proved to be an important tool for the study of planetary atmospheres. The wavelength region above 1050Å has been studied extensively by Barth [1966], Barth and Pearce [1966], and Fastie [1963, 1966], using both photometers and scanning monochromators. In the wavelength region below 1050Å only an upper limit to the night sky resonance emission He I λ 584Å and He II λ 303Å [Byram et al., 1961, Boywer et al. 1968, and Young et al., 1968] and a measurement of the Lyman β flux, also by Young et al., has been determined. The shorter wavelength measurements have been limited by the specialized techniques required for research in the XUV. One such technique, upon which the present photometer depends, requires the use of thin unbacked metallic films as the optical filter. An alternative technique has been to deposit the filter material of interest onto a scintillator, thus permitting XUV photon detection with conventional closed multipliers. The difficulty with this approach is that, (1) a low work function cathode is required, resulting in a high dark current and, (2) pinholes are significant since the intense solar radiation at longer wavelengths is difficult to discriminate against with a non solar-blind detector.

The possibility of using dispersing instruments is both scientifically desirable and technically feasible, but the low intensity of the airglow has restricted their application. The primary difficulty lies in the low reflectivity of materials in the XUV.

The present data were obtained with a filter photometer, the filter consisting of a thin unbacked indium film which is transparent in the wavelength interval 750-1000Å. The properties of metallic films and their applications have been summarized by Hunter, Angel and Tousey [1965] and Samson [1967]. The transmission of various thin films in the extreme ultraviolet is shown in Fig. 1. Such films have been previously used in rocket experiments to reduce the long wavelength stray light level in photographic spectra of the solar ultraviolet [Austin et al., 1964; Purcell et al., 1964]

The extreme ultraviolet photometer is shown in block diagram in Fig. 2. The basic elements are the field of view limiter, the optical filter, an open electron multiplier detector, and associated electronics. An ion retardation ring with +28 volts applied prevented ambient positive ions from entering the detector region; ambient electrons were repelled by the high negative potential of the photocathode. Photographs of the instrument are shown in Figs. 3 and 4.

The optical filter consisted of an unbacked indium film, approximately 1500Å thick, supported on a photoetched mesh. The open areas of the mesh were circular holes with a diameter of 2 mils (0.05mm), arranged in a hexagonal pattern with approximately 3 mils (0.075 mm) between centers. The filter was produced by evaporating 99.99% pure indium on to a water soluble sugar aerosol solution. The film was then floated off in distilled water and picked up on a mesh. After drying, the filter and mesh were mounted in a ring. The filter transmission was then measured with a vacuum monochromator. The filter transmission at 834Å was 8%.

The detector used was a Bendix M306 magnetic electron multiplier with tungsten photocathode [Heroux and Hinteregger, 1960; Goodrich and Wiley, 1961; Timothy et al., 1967], operated at 1725 volts and a gain of 3×10^6. The quantum efficiency of the photocathode was approximately 15% at 834Å. The product of the filter transmission T, and photocathode quantum efficiency η as a function of wavelength is shown in Fig. 5. The potentials supplied to the multiplier were determined by the high voltage supply and the resistors R_1 and R_2 (Fig. 2). These resistors were chosen to optimize the gain of the multiplier and to minimize the effect of magnetic shielding.

The field limiter was produced by machining a conical hole in a cylinder of aluminum. On the surface of this cone were machined grooves with sharp edges. The solid angle subtended by the field limiter was 1.7×10^{-2} sterad. The effective area of the detector was $0.32\ cm^2$. In operation, the field limiter was not as successful as would be desired. Direct sunlight scattered by the field limiter was seen to be present. The intensity of this component was not sufficient, however, to drive the system off scale, thus measurements of the O II dayglow were obtained.

A linear, scale switching electrometer, Keithley Instruments Model 20400, was used to measure the anode current. Two ranges, differing by a factor of ten in sensitivity were available. The sensitivity of the most sensitive range was 10^{-10} amperes per volt. The bandwidth of the amplifier was made purposely large in order to see any spin modulation of the signal. The bandwidth was about 5 kHz.

High voltage for the electron multiplier was obtained from a Packard Bell high voltage power supply. Some ripple was present on the output which was found after the flight to be due to the resistor between the batteries and the input to the power supply. Apparently this model power supply requires that the spacecraft power supply have a very low source resistance. The ripple caused no effects on the data, however.

The instrument was launched on 9 April 1968 at 21 h 26 m GMT (4:26 P.M. local time) aboard a Javelin rocket, NASA 8.40, from Wallops Island, Virginia. The solar zenith angle at that time was about 78°. The instrument viewed along the axis of the rocket, which was oriented 30° from the zenith. The peak altitude attained was 856 km.

Due to a delayed turn-on, dayglow observations were limited on the upward pass to the region near apogee while complete data are available on the downward trajectory. A d-c offset in the data was clearly due to scattering of solar radiation from the field of view limiter. This effect was indicated in the modulated signal associated with the precession of the vehicle as it entered the dense lower atmosphere. The data presented in the following section have this component removed so to give zero intensity at apogee. No evidence was found for a component peak at 300 km, the height of the F2 maximum at that time, hence the signal detected was purely optical. With the wide bandwidth of the amplifier and shot noise from the photoemission process, the data obtained were noisy. Suitable filtering and averaging was used to remove this noise.

III. DAYGLOW OBSERVATIONS AND ANALYSIS

Fig. 6 shows the apparent emission rate observed as a function of altitude. The intensity units are based on the sensitivity at 834Å. For other wavelengths, the intensity must be increased by a factor inversely proportional to the sensitivity at that wavelength relative to 834Å. The salient features of the measurements are the O II λ 834Å resonance radiation observed in the upper portion of the trajectory, and a lower altitude component for which arguments will be given to indicate that this feature is due to photoelectron excited atomic oxygen.

The resonance transition of singly ionized atomic oxygen, $2s^2sp^3\ {}^4S^o_{\frac{3}{2}} \rightarrow 2s2p^4\ {}^4P_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}$, consists of three lines occurring at 832.754, 833.326, and 834.462Å. The lines of this multiplet have been resolved in photographs of the XUV solar spectrum [Tousey, 1963]. Photoelectric measurements for this multiplet, blended with O III lines, have been obtained [Hinteregger et al., 1965]. The flux reported for this feature is 5.4×10^8 photons cm^{-2} sec^{-1}, but it is not known what proportion of this is the O II contribution, nor are the widths of the individual lines known.

The column density of atomic oxygen ions in the atmosphere is large enough to produce a scattering medium that is optically thick at the line centers. Hence, multiple scattering will occur and one must examine the radiative transfer problem in order to predict the intensities of this component of the XUV dayglow. For the moderate optical thicknesses and low densities encountered here, the scattering will take place in the Doppler core of the line, with the frequency redistribution being determined by the Doppler effect of a moving scatterer, first formulated by Henyey [1940]. It has been shown by Jefferies and White [1960], that for these conditions, the frequency redistribution is completely incoherent, with complete redistribution over the Doppler profile of the gas. The radiative transfer problem in this approximation has been extensively studied by Holstein [1947], Donahue and Meier [1967], Tohmatsu and Ogawa [1964] and Tohmatsu and Fujita [1966]. Since the ground state levels of the O^+ atom are degenerate, we can consider each component of the multiplet separately. We assume a plane parallel atmosphere, and assign at each altitude z, an optical depth τ determined by

$$\tau = \sigma_o \int_z^\infty n(z')\,dz' \qquad (1)$$

where n(z) is the number density of oxygen ions at the altitude z,

σ_o is the scattering cross section at the line center,

$$\sigma_o = \frac{\pi e^2}{mc^2} \frac{f_{abs}}{\sqrt{\pi}\,\widetilde{\Delta\nu}} \quad (2)$$

with f_{abs} being the oscillator strength for the line and $\widetilde{\Delta\nu}$, the Doppler width of the scattering gas, expressed in cm^{-1}. Radiative transfer calculations, as developed by Holstein, Donahue, and Tohmatsu, proceed by computing the excitation rate density $4\pi J(\tau)$, which satisfies the integral equation

$$4\pi J(\tau) = 4\pi J_o(\tau) + \tilde{\omega} \int_0^{\tau_o} 4\pi J(\tau') H(|\tau - \tau'|) d\tau' \quad (3)$$

The integral is from the top, $\tau = 0$, to the lower altitude limit of the scattering atmosphere, $\tau = \tau_o$. The parameter $\tilde{\omega}$ is the atomic scattering albedo, and represents the fraction of excitations that result in emission of the line of interest. The function $4\pi J_o(\tau)$ is the rate of primary excitation, in this case, the initial scattering of the solar flux. If the solar zenith angle is $\cos^{-1}\mu_o$, then

$$4\pi J_o(\tau) = \pi F \frac{\widetilde{\Delta\nu}}{\widetilde{\Delta\nu}'} T(\tau/\mu_o) \quad (4)$$

where πF is the incident solar flux and $\widetilde{\Delta\nu}'$ is the Doppler width of the solar line. The functions $T(\tau)$ and $H(\tau)$ are tabulated by Tohmatsu and Ogawa [1966] and Ivanov and Shcherbakov [1965 a,b].. Solution of the integral equation (3) for the excitation rate density $4\pi J(\tau)$ must be done numerically. When this is obtained, the intensity of the dayglow $4\pi I$ is found from

$$4\pi I(\tau) = \tilde{\omega} \int_{\tau} 4\pi J(\tau') T\left(\left|\frac{\tau-\tau'}{\mu}\right|\right) d\tau'/\mu \qquad (5)$$

where $\cos^{-1}\mu$ is the direction of viewing.

Since the dominant ion near the F2 maximum is O^+, assuming electrical neutrality, we can obtain the O^+ distribution below the F2 maximum from the ionosonde data taken at the time and location of the experiment. Extrapolation above the F2 maximum was obtained by fitting an α Chapman distribution to the ionosonde data. Using the oscillator strengths given by Wiese, Smith and Glennon [1966], and with the temperature for the atmosphere found from the α Chapman parameters (1040°K corresponding to a scale height of 55 km), the optical thickness as a function of altitude can be obtained. Attenuation of the radiation by atomic and molecular oxygen in the lower atmosphere limits the total optical depth of the scatterers. Adopting 100 km as the effective lower limit of the scattering region, the total optical depths for scattering of the O II $^4S_{\frac{3}{2}}$ - $^4P_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}$ components are 2.6, 5.5, and 7.7 respectively.

With these total optical depths, and the geometric factors appropriate to the conditions of the experiment, the radiative transfer equation was solved for each component of the multiplet. By assuming that the intensity ratios of the three O II components of the solar line were proportional to their multiplicities, the weighted dayglow intensities were added to give the relative altitude dependence of the brightness of the O^+ resonance multiplet. These calculations are shown as the solid curve in Fig. 3, and are normalized to the experimental observations in the upper altitude range.

The peak intensity of this dayglow feature, found from the normalized curve, is about 160R. This magnitude for the O II dayglow implies that the incident solar line is only a few times wider than the Doppler width of the atmospheric gas. Indeed, we can use these dayglow measurements and the fluxes reported by Hinteregger et al. to estimate the solar line widths. In attempting to do so, however, one must note that the O II fluxes reported by Hinteregger et al. were not corrected for resonance line absorption by the ionospheric O^+ ions above the solar spectrometer. Of course, if the solar line is many times broader than the profile of the absorbing gas, this absorption is insignificant. The observations reported here, however, indicate that one should account for this absorption. Assuming that the solar line profiles are Gaussian in shape, and using nominal ionospheric densities to correct the solar flux measurements, we find that the ratio of the solar Doppler width to that of the ionospheric gas is about 4. This would correspond to a chromospheric gas kinetic temperature of 16,000 ^{o}K or a root mean square velocity of 5 km/sec. These figures are a factor of 4 or 5 less than one might expect based on turbulance velocities observed in the upper chromosphere. However, considering calibration difficulties† and other uncertainties in this spectral region, in addition to the rather imprecisely known physical conditions in the chromosphere, these results are perhaps not unreasonable.

We conclude that the agreement of the data with the theoretical prediction is quite good for altitudes greater than 500 km. The deviation below 500 km is reasonably interpreted as additional components of the dayglow in the pass band of the instrument.

To investigate this part of the data, the theoretical O II dayglow was subtracted, giving approximately the dashed curve in Fig. 6. The scale height of this component is about 58 ± 5 km. Since the scale height of atomic oxygen is of this order, the observed scale height suggests that atomic oxygen is the major emitting species observed. As the O I λ 1304Å multiplet has been observed in the dayglow spectrum, due to some extent to the resonance scattering of the incident solar flux [Donahue and Fastie, 1964], one is tempted to look for the corresponding process in the

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† We estimate our absolute calibration is accurate to within a factor of two.

wavelength region of the present investigation. While no neutral atomic oxygen lines are present in the solar spectrum in this interval, the hydrogen Lyman β line is in near exact coincidence with the ^3P - $^3D^o$ transition of atomic oxygen. The atomic albedo for this line, however, is found to be about 0.6, using the transition probabilities given by Wiese, Smith and Glennon [1966], the competing process being emission of the 11,287Å line. Therefore, very little amplification due to radiation imprisonment is possible, and one can roughly estimate the intensity to be expected on the basis of single scattering. In doing so, one finds about 100 R maximum, far too small to account for the observations.

An attractive alternative to a resonance scattering process is photoelectron excitation. In the high altitudes, the rate of production of photoelectrons is roughly proportional to the total number density, and, since the photoelectrons are constrained to gyrate about the magnetic field lines, the loss rate of photoelectrons at the same altitude will be approximately proportional to the product of the number of photoelectrons and the number density of the gas. Thus, the photoelectron density should be approximately independent of altitude. A scale height of 58 km again implies emissions due to atomic oxygen. While the ionization potential of atomic oxygen is 13.615 eV, corresponding to about 911Å, emissions from states above the ionization limit have been observed in the laboratory, two strong ones occurring at 811Å and 878Å. Tohmatsu [1967] calculates that photoelectron excitation of these lines should contribute about 100 R to the ultraviolet dayglow. Several other emission lines of atomic oxygen are possible contenders, in particular the 936Å ($^1F^o$ - ^1D), 989Å ($^3D^o$ - ^3P), and 999Å ($^1P^o$ - ^1D) lines. Indeed, Green and Barth [1967] calculate 900 R for the 989Å line.and 360 R for the 999Å line, both under photoelectron excitation. The most probable situation is that the observed intensity is composed of several of the mentioned lines.

Although we have argued, on the basis of the scale height, that the principle feature in the lower altitude data is due to atomic oxygen, it should be noted that molecular nitrogen emission bands could also be present. Laboratory spectra of molecular nitrogen show many emission bands in this region of the spectrum [Tilford and Wilkinson, 1964] but the characteristics of the upper states are generally not known. For many of the states observed, only one vibrational level has been found, the actual vibrational quantum number being unknown. Green and Barth have calculated the emission rates from a few of the levels of N_2 under photoelectron excitation in the dayglow. They give 8.9 kR for the emission rate from the b $^1\Pi_u$ state. This can appear in the Birge-Hopfield or the longer wavelength Janin bands. The relative amount appearing in each is uncertain. Green and Barth also considered the h $^1\Sigma_u^+$ state; they given 4.2 kR as the emission rate, appearing in the Watson-Koontz bands and Herman-Gaydon bands. It is known that the h state predissociates [Tilford and Wilkinson, 1964]; this may alter the calculated value. Green [1968] has recently commented that an intense N_2 extreme ultraviolet dayglow could explain an apparent discrepancy between his calculations and the observed intensities of the Lyman= Birge-Hopfield (LBH) bands. His suggestion was that direct transitions to the ground state, rather than cascading to the a state, would bring the calculated and observed LBH intensities into better agreement. While there is no strong indication for this process in the present experiment, based on a scale height argument, one cannot rule it out completely as the known wavelengths of emission from these states are near the long wavelength limit of the optical filter.

IV. SUMMARY

In the present program it has been shown that an XUV thin film filter photometer is a highly effective means of measuring atmospheric dayglow. The instrument has a high optical aperature and reasonable wavelength resolution, as required for rocket investigations of the airglow. The results obtained on this first survey flight are quite reasonably interpreted in terms of O II airglow in the upper atmosphere and photoelectron excited O I in the lower atmosphere. The observed apparent emission rate, apart from a multiplicative factor, agrees well with that determined on this flight by Professor Donahue using a completely independent method. This agreement, in addition to a physically sensible interpretation, is encouraging.

A number of further experimental data are required, however, to improve existing airglow measurements. For example, to calculate the apparent emission rate, it is necessary to know the number density of the scattering specie. To compare the present experimental results with radiative transfer theory it was necessary to obtain this number density from ionosonde data, extrapolated where necessary using an α-Chapman distribution. This procedure is somewhat questionable and it is highly recommended that a plasma probe be included on future rocket flights.

There are also uncertainties in the solar line widths in the XUV. The data now available generally only provide upper limits on the line widths. In the interpretation of the work reported here, it is suggested that the members of the solar O II resonance multiplet may be relatively narrow, perhaps only four or five times the absorption width of O II in the earths atmosphere. This further implies an rms chromospheric turbulence velocity at the source of the O II emission of only 5 km/sec. Such results are, however, somewhat surprising and require further investigation.

Finally, the source or sources of the dayglow in the lower atmosphere have not been uniquely established. Though emission from photoelectron excitation O I is strongly suggested as the dominant feature, additional constituents may also contribute to the dayglow This question can readily be resolved by increasing the number of photometer channels to significantly improve the spectral resolution.

In brief, the data from this flight have provided the basis for a number of significant conclusions regarding both the earths atmosphere and the solar chromosphere. Thus, a comprehensive program in which all significant atmospheric species will be photometrically observed, with high spectral resolution, is highly recommended.

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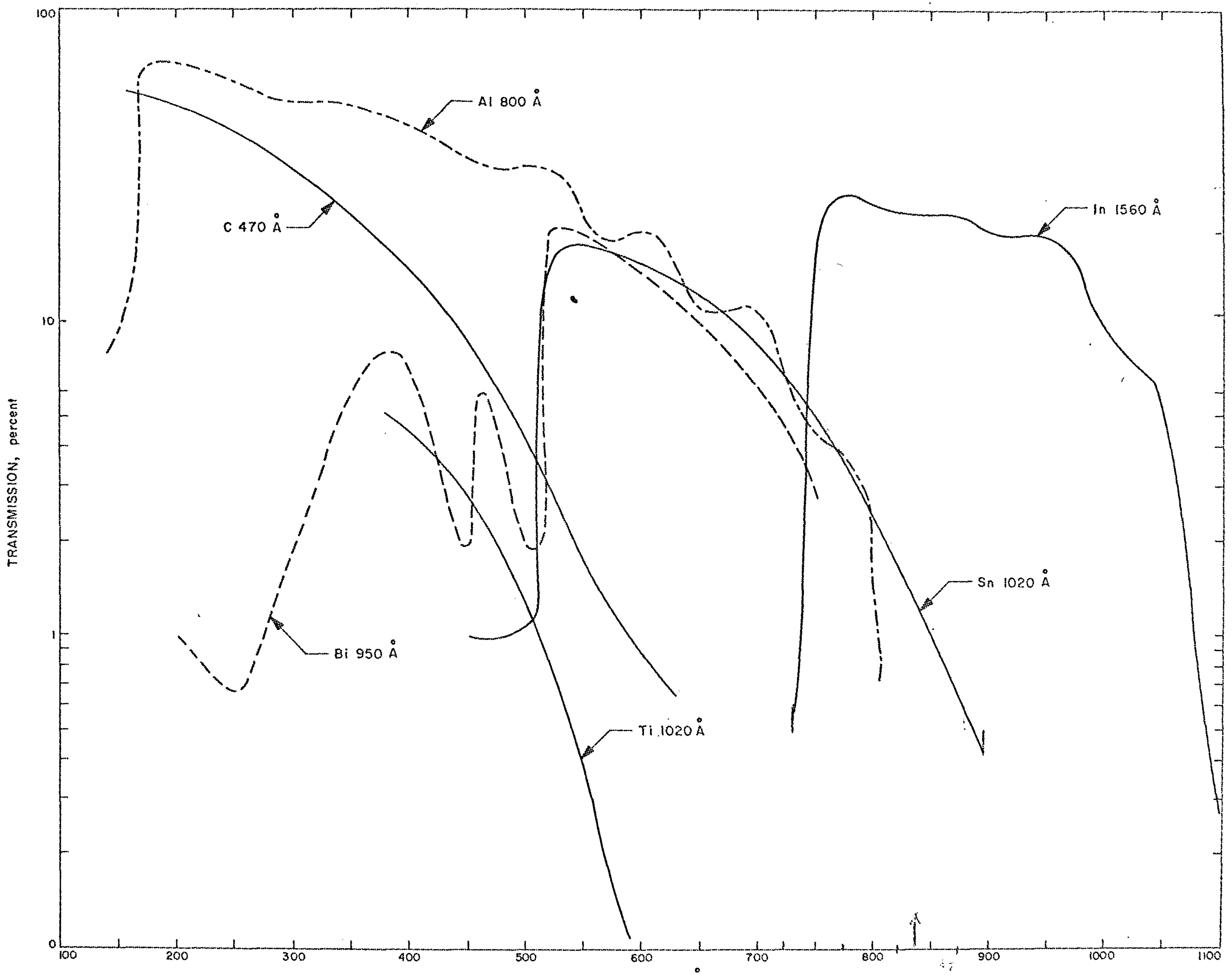
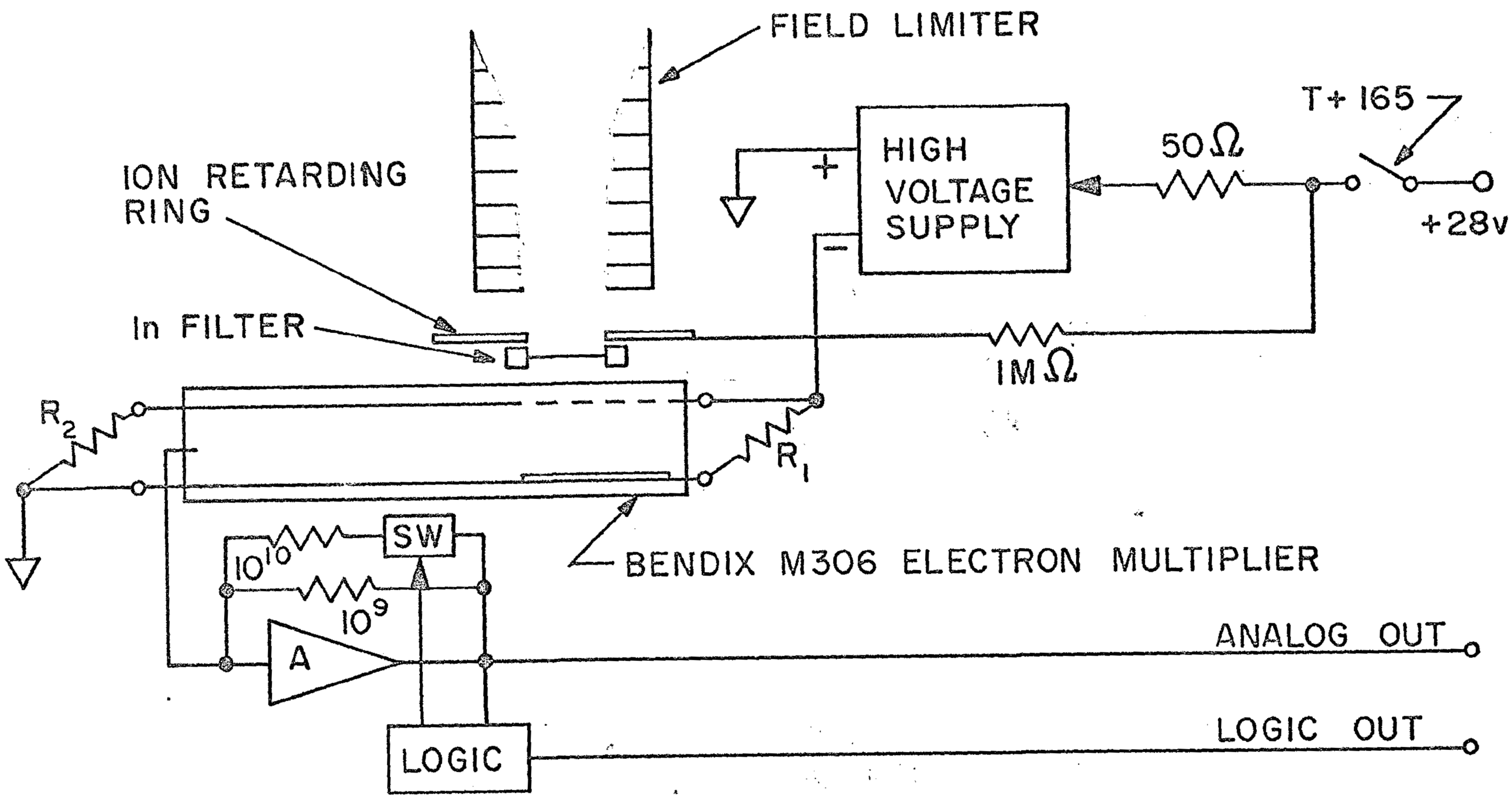


Fig. 1. The transmission of various materials in the extreme ultraviolet.



JAVELIN 8.40 O$^+$ λ834Å PHOTOMETER

Fig. 2. Block diagram of the extreme ultraviolet photometer. Solid angle of the photometer was 1.7×10^{-2} sterad, and the effective area of the detector was 0.32 cm^2. The multiplier was operated at 1725 volts and a gain of 3×10^6. Ambient ions and electrons were repelled by an ion retardation ring at +28 volts and the high negative potential of the photocathode respectively.

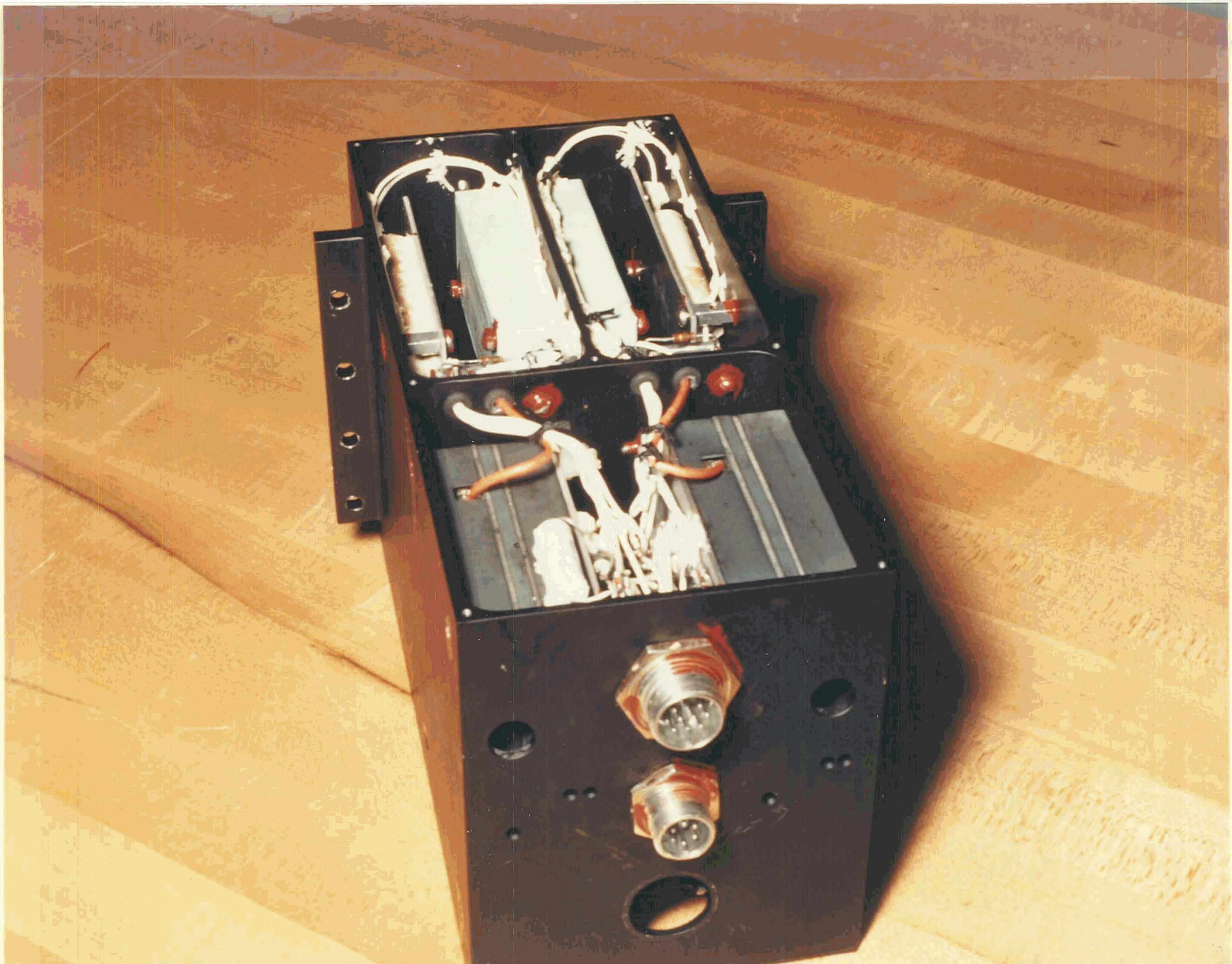


Fig. 3. A view of the flight instrument with one of the side panels removed. The lower portion of the instrument housing contains the electrometer amplifiers while the upper compartment contains the high voltage power supply, the lower voltage mercury cell supply, the electron multipliers and the filter assemblies.

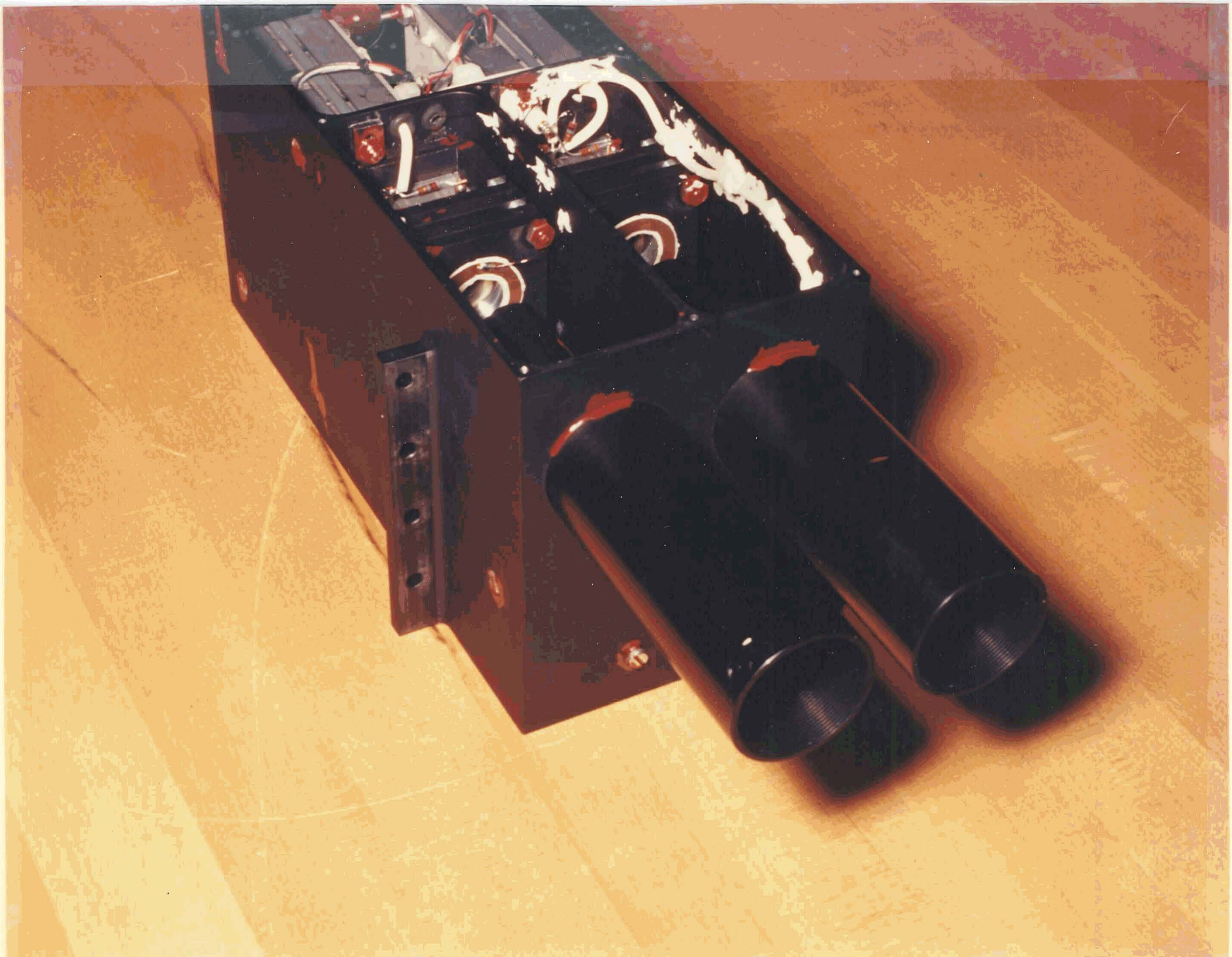


Fig. 4. The flight instrument showing the filter assemblies, electrometer amplifiers and the cylindrical sunshades and field of view limiters for the two channels. The filter assemblies are mounted in the circular discs in the compartment immediately behind the field of view limiters. The open side shown in covered with a panel prior to flight.

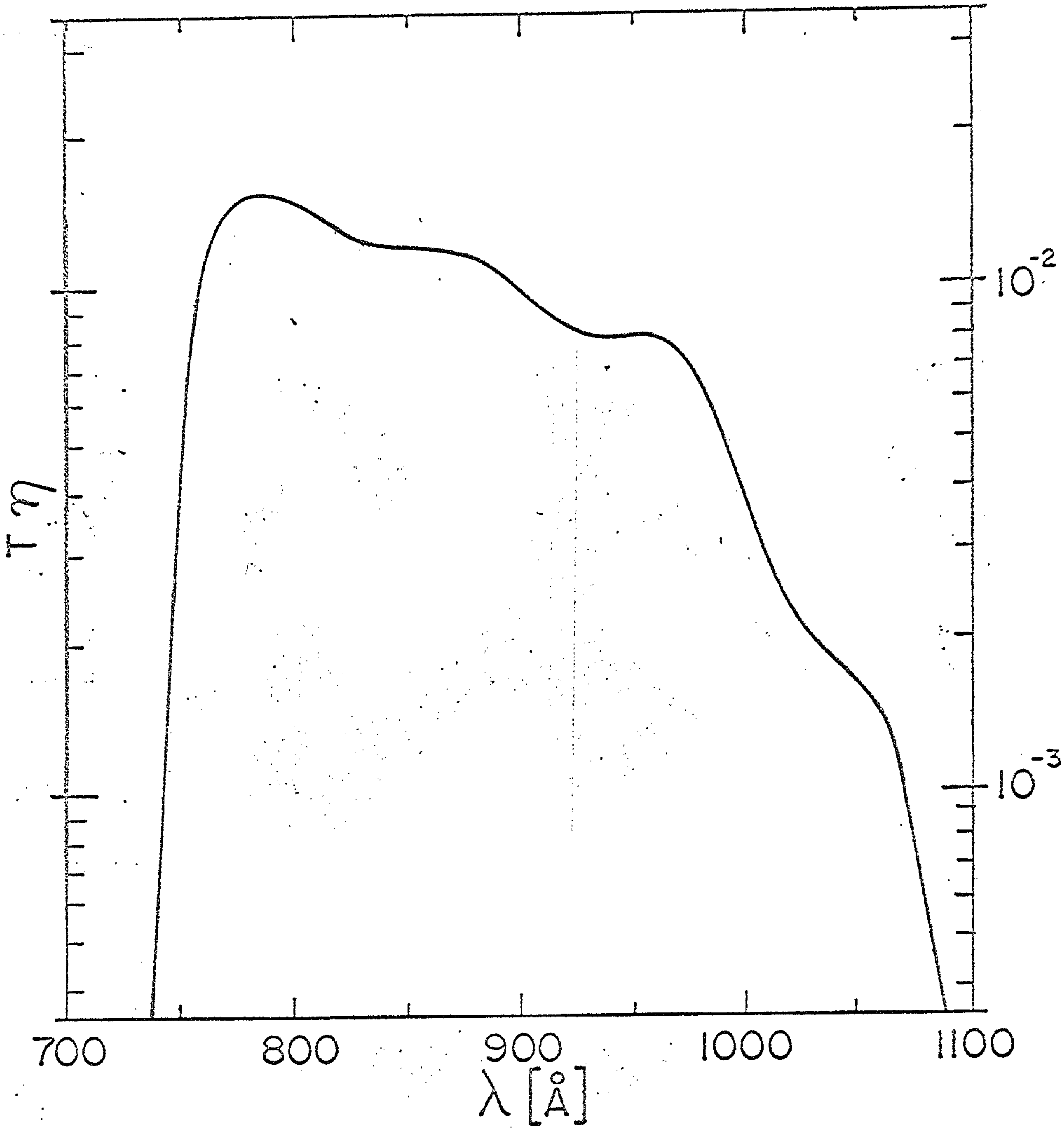


Fig. 5. The product of the transmission of the indium film and the quantum efficiency of the tungsten photocathode. The film was supported on a stainless steel photoetched mess of 0.002 inch diameter holes arranged in a hexagonal pattern with 0.003 inch between centers. The curve includes the transmission of the supporting mesh. The results in Fig. 6 are based on the sensitivity at λ834Å.

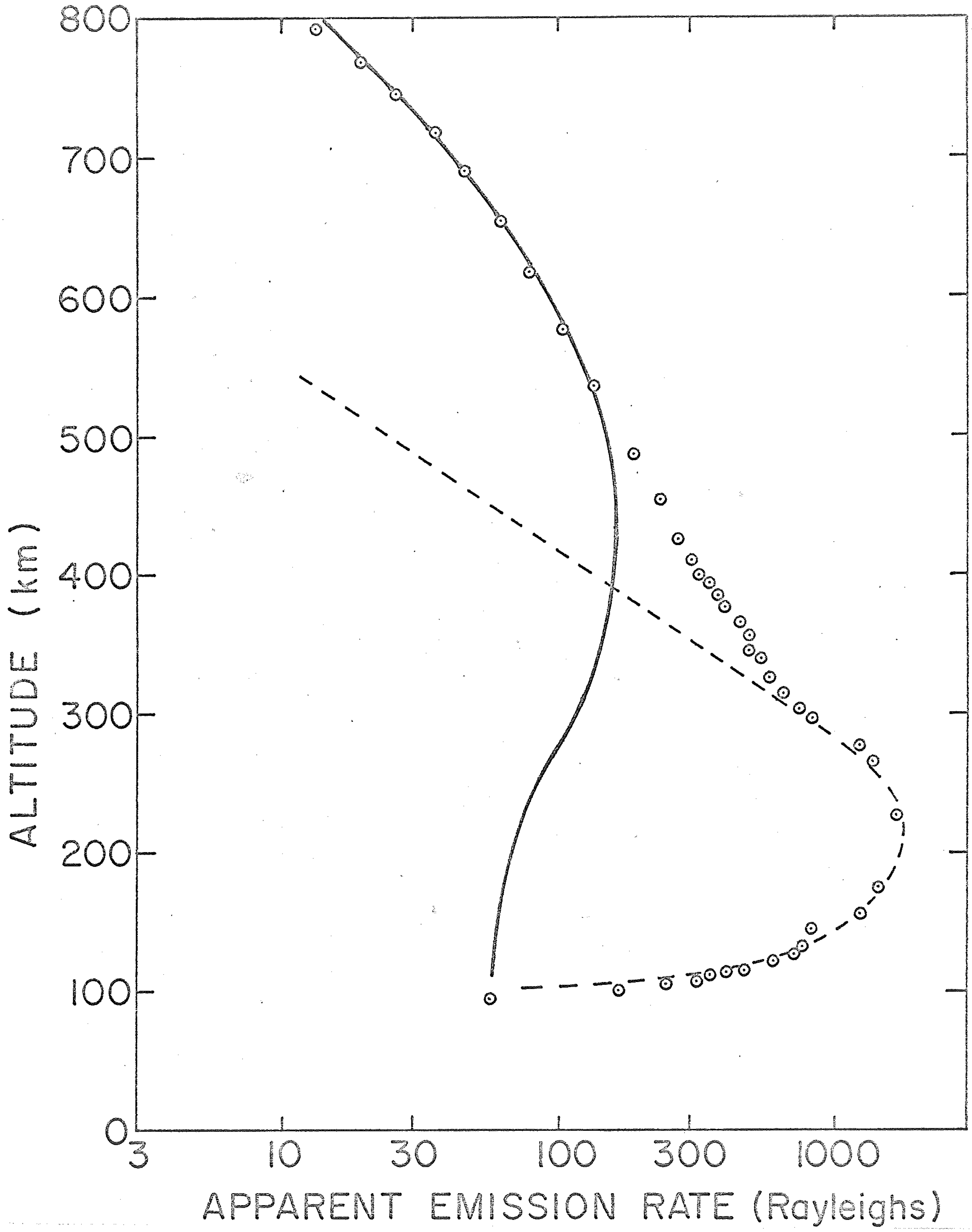


Fig. 6. The extreme ultraviolet dayglow observations. The data in the upper altitudes represents the resonance dayglow of the oxygen ion at λ834Å. The solid curve is a theoretical model of this feature. The dashed curve is the difference between the observations and the theoretical calculations, and is interpreted as emissions due to photoelectron excited atomic oxygen.