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Absolute flux measurements in the rocket ultraviolet

by

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FOREWORD

The spectrometer used for this experiment is similar to the one flown on Mariner Mars Orbiter (Mariner IX) in 1971. The goal was to calibrate some stars in absolute value so that orbiting spectrometers could be recalibrated in flight.

D. Frimout was a ESRO post doctoral fellow at Laboratory for Atmospheric and Space Physics of the University of Colorado when he contributed to this work. This paper was published in Astronomy and Astrophysics, Vol. 30 (1974) pp. 127-134.

AVANT-PROPOS

Le spectromètre utilisé pour cet expérience est identique à celui qui a servi pour le vol Mariner Mars Orbiter (Mariner IX) en 1971. Le but de cet expérience était d'étalonner des étoiles en valeur absolue afin de pouvoir récalibrer des spectromètres en orbite.

D. Frimout était le tenant d'une bourse ESRO au Laboratory for Atmospheric and Space Physics de l'Université de Colorado, quand il a contribué à ce travail. Ce texte a été publié dans Astronomy and Astrophysics, Vol. 30 (1974) pp. 127-134.

VOORWOORD

De spectrometer die voor dit experiment gebruikt werd, is identiek aan deze gelanceerd met Mariner Mars Orbiter (Mariner IX) in 1971. Het doel van dit experiment was bepaalde sterren te ijken in absolute waarde zodat UV spectrometers in orbit opnieuw kunnen geijkt worden in vlucht.

D. Frimout was houder van een ESRO postdoctorale beurs bij het Laboratory for Atmospheric and Space Physics aan de universiteit van Colorado, als hij aan dit project meewerkte. De tekst werd gepubliceerd in Astronomy and Astrophysics, Vol. 30 (1974) pp. 127-134.

VORWORT

Der Spektrometer, der in diesem Experimenten gebraucht wurde, ist das selbe Instrument, das auf Mariner IX geflogen wurde. Dieses Experiment sollte absolute Eichung gewissenen Sternen machen, so dass die satellisierten Instrumenten wieder gekalibriert könnten sein.

Während seines Verweilen zur Colorado Universität (USA) mit Hilfe eines ESRO Stipendium hat D. Frimout zu dieser Arbeit beigetragen. Dieser Text wurde in Astronomy and Astrophysics 30, 127-134, 1974 herausgegeben.

ABSOLUTE FLUX MEASUREMENTS IN THE ROCKET ULTRAVIOLET

by

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Abstract

A two-channel spectrometer was calibrated in the wavelength region 1200-3400 Å and flown on an Aerobee rocket to observe the stars α Lyr, η UMa, and ζ Oph. Standard tungsten lamps provided the absolute calibration down to 2250 Å and a photodiode calibrated by the National Bureau of Standards was the reference at shorter wavelengths. The molecular branching-ratio technique of relative calibration using the gases CO, NO, and N_2 was a check on the absolute calibration. The flux from η UMa agrees with the prediction of a hydrogen line blanketed model atmosphere within 10% between 1700 and 3400 Å and within 4% over most of this wavelength region.

Résumé

Un spectromètre à deux caneaux, calibré dans le domaine de longueur d'onde de 1200 à 3400 Å a été lancé avec une fusée Aerobee pour observer les étoiles α Lyr, η UMa et ζ Oph. Une lampe standard à tungstène donnait la calibration de 3400 Å à 2250 Å et une photodiode, calibrée par le National Bureau of Standards était la référence pour des longueurs d'ondes plus courtes. Un étallonnage relatif par la méthode des rapports des branchements moléculaires en utilisant les gaz CO, NO et N_2 a été effectué comme vérification de la calibration absolue. Le flux mesuré de η UMa correspond à 10% près avec les prédictions pour un modèle d'atmosphère avec noircissement des raies d'hydrogènes entre 1700 et 3400 Å. La précision est même supérieure à 4% pour la plus grande partie du domaine de longueur d'onde.

Samenvatting

Een tweekanalen spectrometer, geijkt in het golflengte gebied van 1200 tot 3400 Å werd met een Aerobee raket gelanceerd met als doel het waarnemen van de sterren α Lyr, η UMa en ζ Oph. Een standaard tungsten lamp gaf de absolute ijking van 3400 tot 2250 Å en een fotodiode, geijkt door het National Bureau of Standards was de referentie voor de lagere golflengtes. Een relatieve ijking met de moleculaire vertakkingsverhouding techniek gebruikmakend van de gassen CO, NO en N_2 was een proef op de absolute ijking. De gemeten flux van η UMa stemt overeen met de voorspellingen voor een atmosfeermodel met waterstoflijn zwarting met een nauwkeurigheid van 10% tussen 1700 en 3400 Å en zelfs beter dan 4% over het grootste gedeelte van het golflengte gebied.

Zusammenfassung

Ein Doppelkanalspektrometer, der zwischen 1200 und 3400 Å geeicht wurde, wurde mit einer Aerobee Rakete um die Sterne α Lyr, η UMa und ζ Oph zu beobachten, geschossen. Eine Standardwolfframlampe wurde für die Eichung zwischen 3400 und 2250 Å benutzt. Eine durch des NBS geeichnete Fotodiode wurde als Referenz für die kürzere Wellenlänge gebraucht. Eine relative Eichung mit Hilfe der Methode des molekularen Verzweigungsverhältnis wurde mit CO, NO und N_2 als Prüfung der absolute Eichung durchgeführt. Der gemessene Fluxx von η UMa stimmt auf 10% mit einem atmosphärischen Model, wo die Wasserstofflinien zwischen 1700 und 3400 verdüstert sind, überein. Die Genauigkeit ist besser als 4% über dem grösste Teil dieses Wellenlängegebietes.

INTRODUCTION

Accurate measurements of stellar fluxes in the far ultraviolet are of fundamental importance to our understanding of the atmospheres of early-type stars and of the energy input to the interstellar medium. If the flux distribution of just one non- variable star were well known, data from satellites such as OAO-2 can be used to transfer the calibration to other objects in the sky. A sounding rocket is better than a satellite for obtaining reliable data, because the flight instrument may be calibrated before and after flight, and because the exposure time of the flight optics to contaminants can be minimized.

On 14 July 1972 Aerobee 13.004 was launched from the White Sands Missle Range with a scanning spectrometer, which was carefully calibrated before flight. Observations of α Lyr, η UMa, and ζ Oph were obtained, and the spectrometer was recovered in good condition. Before presenting the results for η UMa, the calibration techniques are discussed in detail. Section II describes the spectrometer and data handling methods, and Section III includes the results of the three basic calibrations. In Section IV the observed flux for ηUMa is presented and compared to other observations and a model atmosphere. A critical evaluation in Section V concludes the article.

II. INSTRUMENTATION

The basic instrument used for this experiment is similar to the ultraviolet spectrometers that Mariner 6, 7, and 9 carried to Mars in 1969 and 1971 (Pearce *et al.*, 1971). The rocket spectrometer (UVS) is an Ebert-Fastie monochromator with a collecting telescope of 3.8 by 6.4 cm effective aperture and a focal length of 25 cm. Two channels obtain spectra in the wavelength range 1150-3400 A using EMR 541-G and -F photomultipliers. The G-channel has a lithium fluoride window and a cesium iodide cathode which restricts the useful coverage to less than 2000 Å. The primary, secondary, and Ebert mirrors and grating are all coated with magnesium fluoride which limits the short wavelength sensitivity to about 1150 Å. The F-channel has a sapphire window and a cesium telluride cathode with a long wavelength cutoff near 3400 Å. The short wavelength sensitivity of the F-channel is limited to about 1700 Å by a suprasil quartz periscope that transfers the spectral image from the focal plane to the detector.

The grating has 2160 lines mm^{-1} and is blazed at 2000 Å in first order. A cam drives the grating through one complete scan and flyback to the starting point once every three seconds. Pulse-counting electronics with an integration time of 6.25 ms divide an individual spectrum into 480 sample points. The exit-slit widths are ~ 18 Å, and samples are taken every 5.5 Å as the spectrum moves past the exit slits. The number of pulses in each 6.25 ms sample is counted and sent to the telemetry system as a sequence of 8 bits followed by a synchronization pulse. A fiducial is placed at the beginning of each scan. For calibration all data taken in the laboratory were recorded on line tape using a PDP-12 computer. A special program allowed the summing of scans in real-time to improve the signal-to-noise ratio.

The spectra were monitored on a visual display screen as the data stream entered the computer. The calibration data were then transferred from the linc tape on the PDP-12 to standard computer tape on a PDP-8 system. The reduction was completed using the University of Colorado CDC-6400 computer and the Mariner Mars spectrum editor system on the PDP-8 (Stern *et al.*, 1972).

III. CALIBRATION

a) Field of View

For observations of point sources the most direct calibration procedure is to use collimated light for the calibration source. The amount of divergence permitted in the laboratory beam is determined by the instrumental field of view shown in Fig. 1. These measurements were made for the F channel using a well collimated beam from a tungsten source. The grating scan was stopped at the peak of the response near 3000 Å, and pulses were counted as the UVS was rotated about two orthogonal axes. The response varies by ± 4% over the central 8' in the dispersion direction. Both profiles are taken across the center

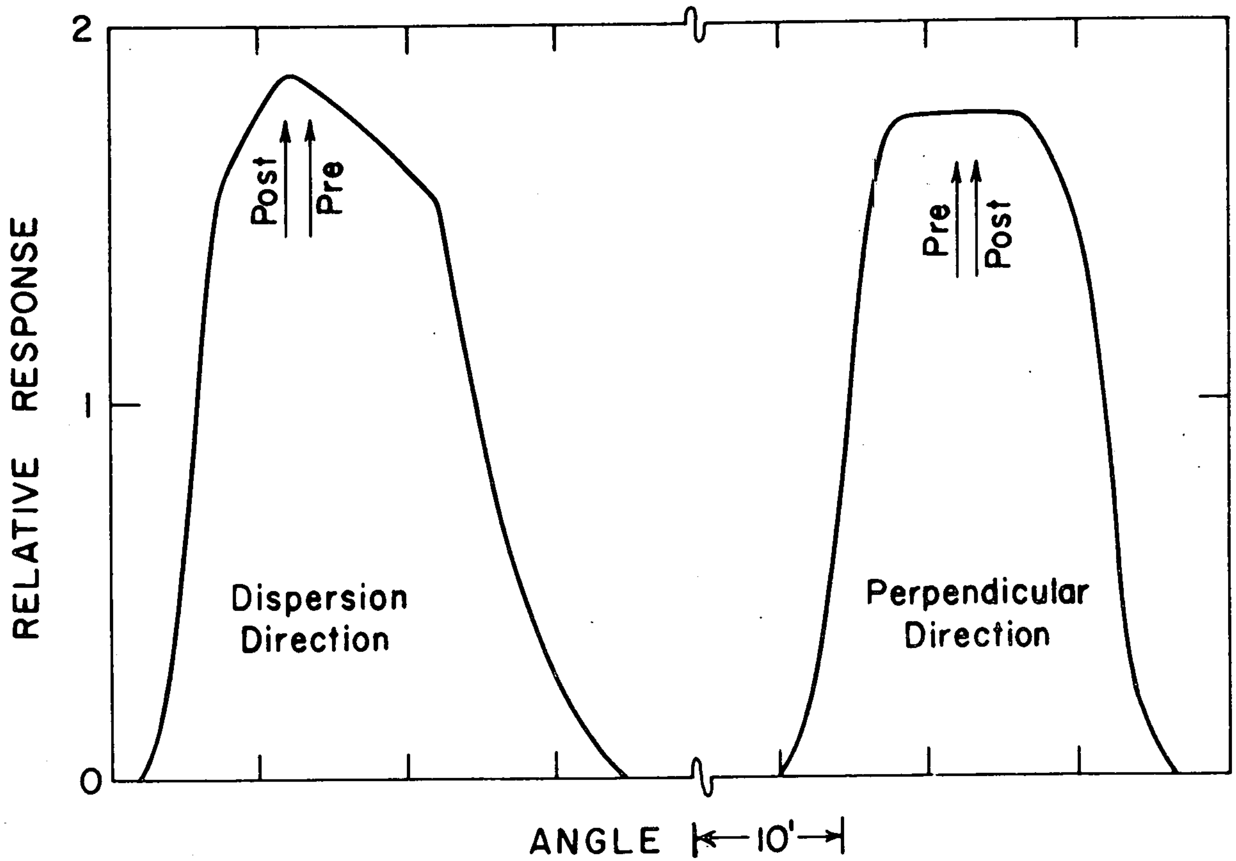

Fig. 1.- Field of view measurements for the UVS in two orthogonal directions centered on the circular entrance aperture. The arrows indicate the good agreement between the pre-flight and post-flight alignment of the STRAP III star tracker.

of the circular entrance aperture. The pointing of the UVS was controlled by a STRAP III star tracker which was set before flight to place the stellar image at the arrows labeled "pre" in Fig. 1. The small difference between the directions that the star tracker pointed before flight and at a post-flight alignment check would cause a change change of less than 2% in the response to a point source.

b) Tungsten lamps

Tungsten ribbon filament lamps with calibrations traceable to the National Bureau of Standards provide the best source for absolute calibration down to about 2250 Å. The monochromatic intensity of lamp Q 17 was measured by NBS at a direct current of 38.722 amperes in August 1970 and used for the first time to calibrate Aerobee 13.004. The lamp was placed at a distance of 73 meters from the primary mirror of the UVS in an enclosed hallway. A circular diaphragm was placed in front of the lamp filament to limit the observed area to that calibrated by NBS. If the brightness of the lamp is given in terms of the specific intensity, I in erg cm^{-2} s^{-1} A^{-1} $sterad^{-1}$, outside its window, then the flux at the UVS primary mirror is

$$F(\lambda) = I(\lambda)\, A/r^2 \quad ,$$

and the inverse sensitivity of the instrument is

$$S^{-1}(\lambda) = F(\lambda)/R.$$

R is the response in counts at each sample point, A is the area of the hole in the diaphragm, and r is the hole-to-primary distance (72.53 m). The divergence of the beam over the primary is less than 2' in the dispersion direction and 3' in the perpendicular direction, so that the total flux incident at the primary enters the entrance hole as shown by Fig. 1. The calibration of Q 17 by NBS is given down to 2250 Å.

The same calibration procedure was repeated using another tungsten ribbon lamp, EPUV 119. This time the absolute intensity of the lamp was determined from the brightness temperature at 6530 Å measured with optical pyrometer, number LN 1696807, also calibrated by NBS in August 1970. The brightness temperature determines the true temperature, T, and the specific intensity is the product of Planck's black body formula, B(λT), the transmission of the quartz lamp window (0.90), and the emissivity of tungsten, E(λ,T), given by DeVos (1954). The calibration, S^{-1}, follows from Eqs. (1) and (2). The emissivity is not given below 2300 Å by DeVos, and the values of Buckley (1971) have error bars too large to be useful.

Extinction by air over the 73 m path was greater than 1% below 2900 Å and must be corrected for. Attempts to measure the amount of extinction using a quartz-iodine lamp located at different distances from the UVS were inconclusive, thus requiring calculations of the expected light loss. The Rayleigh scattering cross section used is from Allen (1963), and O_2 and O_3 absorption cross sections are from Hudson (1971). The mean concentration of ozone for the time of day of the calibration (2 A.M., M.D.T.) was measured a year after obtaining the calibration data. The fractional concentration was only 1.4×10^{-8}, and for room temperature and the 0.8 atm pressure in Boulder the maximum correction to S^{-1} is 2.4% at 2550 Å. No significant deviation from the ambient O_3 concentration is present near a tungsten lamp within the brightest part of the beam. The error caused by the possibility of a larger amount of O_3 on the date of the calibration is unlikely to exceed 3%. The total correction factors applied to the inverse sensitivity at 2250, 2400, 2600, and 2800 Å are 0.85, 0.93, 0.96, and 0.98, respectively.

Calibration points computed at 50 Å intervals for the two lamps are shown in the right half of Fig. 2 with the extinction corrections included. The maximum difference between the calibrations from the two lamps is 6% and the data fit a smooth curve. The wavelength scale is based on a least-squares fit of a cubic polynomial to the observed positions of emission lines. The scale was the same before and after the flight and is accurate to ± 3 Å.

c) Vacuum Calibration

No standard source lamps are available for wavelengths below the tungsten range, so that the procedure consisted of transferring the calibration from standard detectors to the

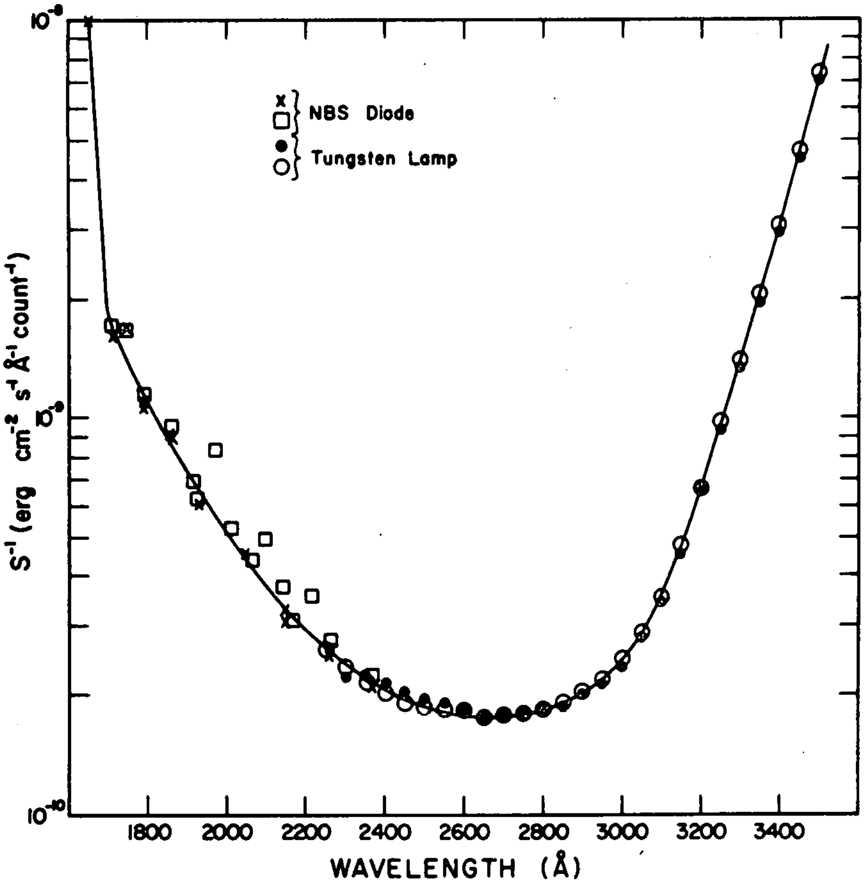

Fig. 2.- Absolute calibration for the F channel (solid line). Pre-flight and post-flight calibrations based on the NBS photodiodes 118 and 141 are indicated by X and □, respectively. Tungsten calibrations based on lamps Q 17 and EPUV 119 are shown every 50 A as ● and ○, respectively.

flight instrument. The basic standard was NBS photodiode 118, which has a magnesium fluoride window and a cesium telluride cathode. This detector was calibrated by NBS from 1164 to 2385 Å in December 1970 and January 1972. During the second calibration, serious non-uniformities of the type discussed by Canfield *et al.* (1973) were discovered in the cathode. Since we used a larger area than the 6 x 6 mm calibrated by NBS, the diode was recalibrated against NBS diode 141 in August 1973. The cathode of diode 141 is uniform, and the comparison utilized the same cathode area and geometry that was referenced earlier for diode 118. Diode 141 was certified by NBS in August 1972, and the calibration was updated in August 1973. The fransfer of the calibration from diode 118 was in two steps: first, from the diode to a standard photomultiplier tube and then to the flight spectrometer. The intermediate standard is necessary, because the photodiode does not amplify the cathode current and cannot measure the low flux levels used to illuminate the primary mirror of the flight telescope during calibration.

1) Transfer to the Standard Photomultiplier

The comparison of a diode and a photomultiplier (PMT) is difficult because a light level necessary for a good signal ($\sim 10^{-11}$ amps) from the diode produces too much current from a PMT with a gain of $\sim 10^6$. To alleviate this problem, the PMT was calibrated and used at only 2500 volts, and a screen with transmission $T = 0.0190$ was placed in front of the PMT to cut down the light level. To calibrate a standard tube, the product of gain, G and quantum efficiency, Q, as a function of wavelength must be determined.

$$GQ = \frac{i_p Q_D}{i_D T} , \tag{3}$$

where i_p is the PMT current, i_D is the diode current, and Q_D is the quantum efficiency of the diode determined by NBS. A stable light source is required to provide the same illumination of both detectors when measuring the currents.

A 1-meter McPherson monochromator with a Hinteregger lamp producing an H_2 spectrum was used in the calibration transfer. The screen transmission was measured in the same geometry (immediately in front of the PMT) in which it was used, because the holes acted as collimators, and the transmission depended on the divergence of the beam. However, the transmission was independent of wavelength and was uncertain by only ± 3%. To assure reproducibility, the PMT, the diode, and again, the PMT were interchanged in a sequence of comparisons at different wavelengths. In order to illuminate a large area of the photocathodes, a vacuum extension tube placed the cathodes about 30 cm behind the exit slit. A 1 cm aperture at the end of the extension insured an underfilling of the diode and PMT, so that the same amount of light illuminated both detectors. Approximately the same area of the PMT cathode was used in the next step of the calibration.

The standard PMT used for the final calibration was an EMR 542-F with a lithium fluoride window and a cesium telluride cathode. Each interchange of the PMT and NBS diode required exposing the tubes to atmospheric pressure, and each time a PMT was pumped down to vacuum there was a delay of a few minutes while the current rosr to a stable value. Flushing the chamber with dry nitrogen each time the tubes were returned to atmospheric pressure largely eliminated this delay for most tubes. Perhaps this variable response was connected with the adsorption and outgassing of water vapor from the lithium fluoride window. An *important corollary* followed: the rocket payload had to be flushed with dry nitrogen up to the time of launch in order to avoid changes in the instrumental response in a 5 minute flight.

2) Transfer to the Flight Spectrometer

The UVS was placed in a large vacuum tank and aligned to a parallel beam of monochromatic radiation supplied by the 1-meter McPherson and a 1.6 m focal length collimating mirror. The standard PMT was mounted on an X-Y beam scanner immediately in front of the UVS telescope. The usual procedure as to sum the response from 10 scans of the UVS, obtain a beam scan, and repeat the 10 scans to assure stability of the light source. The mean incident flux obtained from the beam scan varied by a factor of 3 to 4 across the primary mirror of the UVS. This variation is unimportant as long as the response of the UVS is uniform over the grating and mirrors. The response near 3000 Å was constant to ± 10%.
The mean flux $\bar{F}(\lambda)$ is

$$\bar{F}(\lambda) = \frac{6.24 \times 10^{18}\, \bar{i}}{GQ\, A_{PMT}} \text{ photons cm}^{-2}\ \text{S}^{-1} \quad , \tag{4}$$

where $\bar{i}$ is the mean current from the standard PMT averaged over the acceptance area, GQ is given by Eq.(3), A_{PMT} is the area of the mask on the PMT (1.61 cm^2), and there are 6.24 x 10^{18} electrons in a Coulomb. A convenient measure of the UVS response, R, is the sum of the counts recorded during a scan of the monochromatic line. The calibration for a continuum source is

$$S^{-1}(\lambda) = \frac{h\nu\, F}{R\, \Delta\lambda} \quad , \tag{5}$$

where the photon energy $h\nu$ makes the units erg cm^{-2} s^{-1} A^{-1} $count^{-1}$, and $\Delta\lambda$ is the number of Angstroms between sample points.

The results from the vacuum tank calibration for the F channel are shown in the left part of Fig. 2. A correction to the absolute calibration by a factor of 0.88 is included to make the vacuum calibration with the tungsten calibration in the region of overlap. The probable cause for this difference is discussed in Section V. The normalization to the tungsten calibration means that the present results are independent of any possible multiplicative errors in the NBS calibration of their standard diodes. The post-flight points seem to shown a slight loss of sensitivity (~ 10%) which may have been caused by post-flight contamination. Therefore, the adopted calibration curve shows a small bias towards the preflight results.

d) Molecular Branching-ratio Calibration

The relative emission intensities of the molecular bands from one band system of a diatomic molecule can provide a relative calibration with broad-wavelength coverage (Mumma and Zipf, 1971). The molecular branching-ratio (MBR) method depends on measuring the response of the spectrometer to bands from the same upper vibrational level, ν, with known branching ratios, $A_{\nu'\nu''}$, to each lower level, ν''. A mono-energetic electron beam provides the excitation energy for the band systems. For the MBR calibration, the UVS was placed in the large vacuum tank, separated from the electron beam source by a lithium fluoride window with relative transmission t(λ). A collimating mirror had relative reflectance r(λ). In order to separate the closely spaced band systems, the UVS flight slits were replaced by slits giving a 2 Å resolution, and the scan speed was reduced by a factor of 10. If the photocathode response is uniform over a 18 Å slit width (1.0 mm), these changes should not affect the *relative* sensitivity of the spectrometer

$$S^{-1} = \frac{h\nu\, t(\lambda)\, r(\lambda)\, A_{\nu'\nu''}}{R_{\nu'\nu''}} \tag{6}$$

$R_{\nu'\nu''}$ is the total counts recorded in the band by the UVS.
The fourth-positive bands of CO, the Lyman-Birge-Hopfield (LBH) bands of N_2, and the γ bands of NO were used for the MBR calibration. CO is the most useful gas, because the absence of cascading and quenching permits the calculation of the relative populations of the upper levels, ν'. Consequently, the relative intensities, $A_{\nu'\nu''}$, given by Mumma (1972) allow the immediate comparison of all the fourth-positive bands. For N_2 and NO, the values of $A_{\nu'\nu''}$ in Mumma (1972) apply to bands from the same ν', requiring a fitting together of the calibrations for the groups of bands from the different upper levels, ν'. The groups of bands for N_2 and NO were fitted separately ; the LBH bands were compared to the fourth–positive system ; and the γ bands were compared directly to the absolute calibration (Fig. 3).

The results in Fig. 3 for CO and N_2 cover about the same wavelength range and show no systematic disagreement. The relative calibration between the G channel (open symbols) and the E channel (solid symbols) was preserved, so, in principle, and absolute calibration at just one point would suffice to calibrate both channels. The γ bands of NO are not particularly well suited to the MBR calibration,because the broad bands in parentheses. In view of the scatter in the data, the deviation of the 6 good points from the absolute calibration is not significant. A large part of the scatter in Fig. 3 may be due to the grating drive cam, which is somewhat irregular, causing some lines to be scanned slowly and some rapidly. This scatter should cause no systematic error. The CO and N_2 bands confirm the shape of the

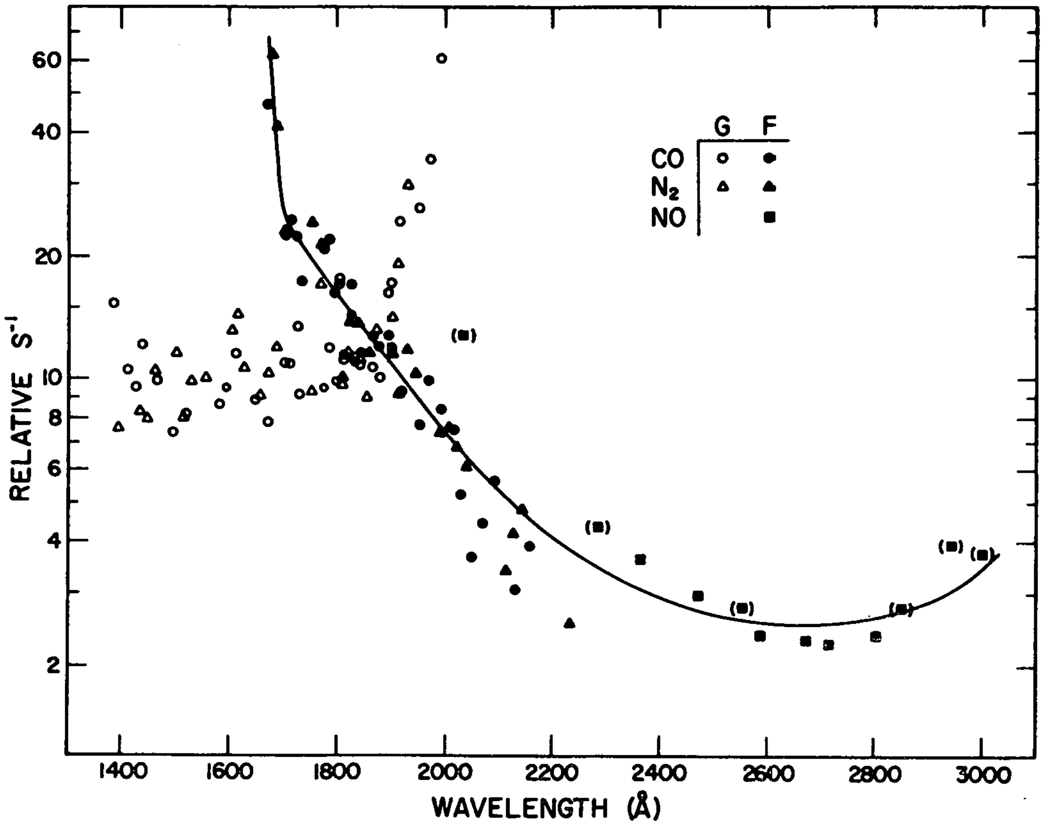

Fig. 3.- Molecular branching-ratio calibration. The symbols for the G and F channels and the 3 gases are indicated on the figure. Parentheses enclose uncertain data points. The solid line is the adopted shape of the absolute calibration from fig. 2.

absolute calibration below 2000 Å. At $\lambda > 1900$ Å the variation of the electronic transition moment with internuclear separation is not well known (Mumma, 1972). At 2100 Å the MBR calibration might possibly be in error by the observed difference of ~ 1.25 between the absolute and MBR calibrations (Lawrence, private communication).

IV. RESULTS FOR η UMa

During the flight of Aerobee 13.004, the G channel obtained no useful data because of high-voltage arcing. The 22 scans of η UMa from the F channel were averaged to find the instrumental response, R, at each sample point, and the stellar flux, F(λ), was computed from S^{-1}, given by the solid line in Fig. 2.

$$F(\lambda) = S^{-1}(\lambda)R \ . \tag{7}$$

The stellar flux at each sample point is shown as a small square in Fig. 4, while the solid line represents the data smoothed twice with a running average of 15 points. The solid line has been corrected for second-order overlap by 2% at 3300 Å and 10% at 3380 Å. Also shown are the photometry of Bless *et al.* (1971) and the OAO-2 results reported by Underhill (1973), using the calibration of Evans (1972). The ground-based spectrophotometry of Schild, Peterson, and Oke (1971) shown in Fig. 4 is placed on an absolute scale by normalizing to $V = 1^{m}_{.}86$ for η UMa and the flux for $V = 0^{m}$ of 3.64×10^{-9} erg cm^{-2} S^{-1} A^{-1} at 5480 Å given by Oke and Schild (1970). The calibrations of Bless *et al.* are based on calculations of the flux from a synchrotron source, while Evans' calibration standards are similar to those discussed in Section III. Our measurement is within 3% of the value of Schild *et al.* at 3300 Å, but such a small difference may be fortuitous in view of the low count rate at the longest wavelengths. However, this confirmation of the ground-based value by a space vehicle is the first known to the authors.

In Fig. 5 the three sets of ultraviolet data are compared to a model stellar atmosphere by Klinglesmith (1971) for an effective temperature of $T_e = 18000°K$, which fits the Paschen continuum and Balmer discontinuity of Schild *et al.* (1971). The model is placed on

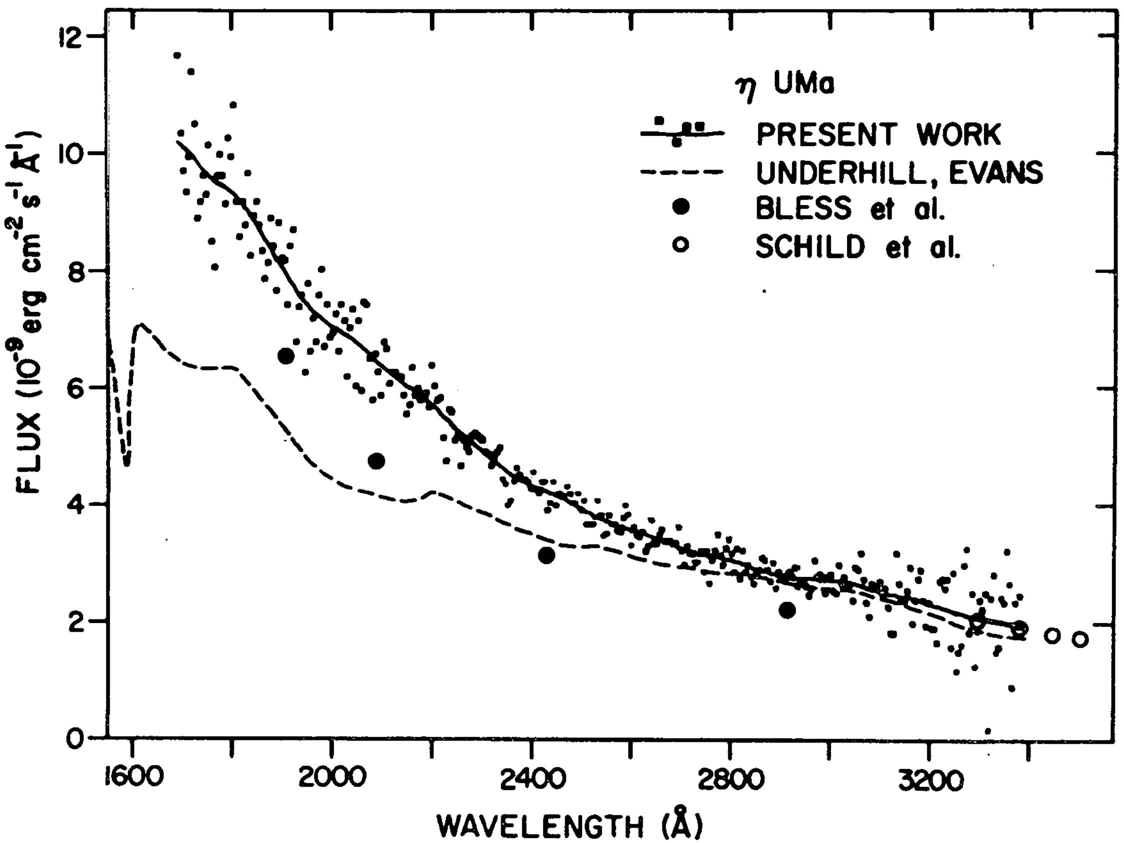

Fig. 4.- Measured flux from the star ηUMa (B 3 V). Small squares and the smooth solid line are the present results. The large filled circles are from Bless *et al.* (1972). The dashed line is from Underhill (1973), derived from the absolute calibration of Evans (1972). The ground-based spectrophotometry of Schild *et al.* (1971) is shown as open circles.

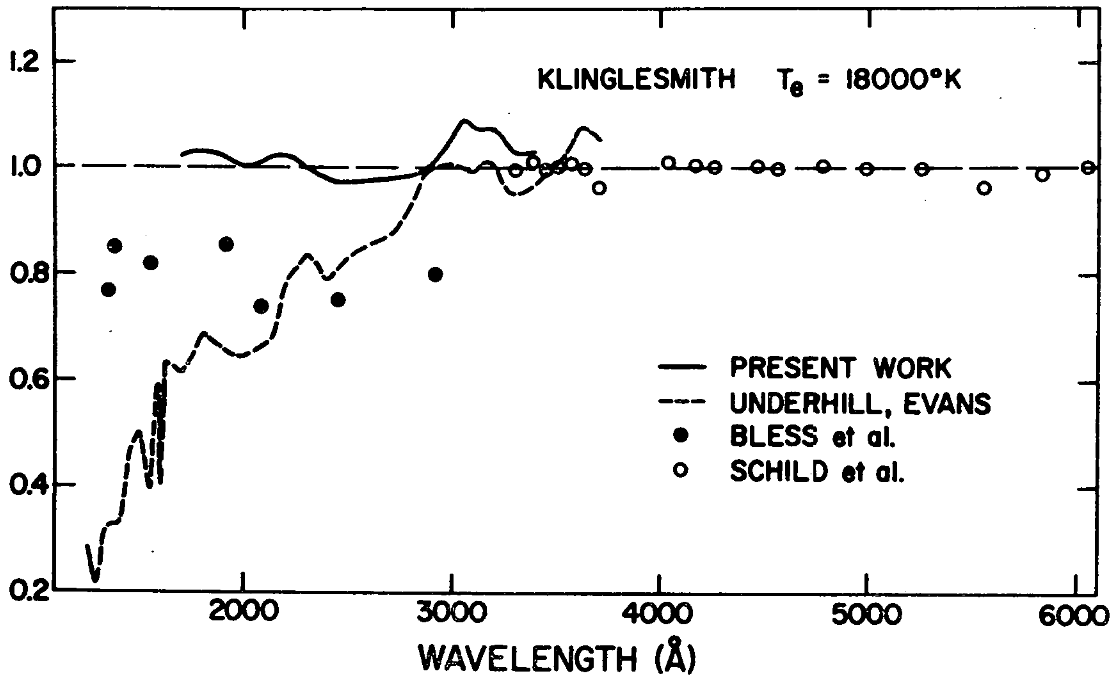

Fig. 5.- Ratios of the data to a hydrogen line blanketed model atmosphere with $T_e = 18000^0$K, $\log_g = 4.0$, 2/3 hydrogen and 1/3 helium by mass, from Klinglismith (1971). The lines and symbols are the same as in Fig. 4. The model was normalized to the observations of Schild *et al.* (1971) longward of the Balmer discontinuity.

an absolute scale by normalizing to the Schild *et al.* values in the 4000 to 6050 Å range, and the absolute theoretical flux is used as the denominator of the ratios computed for the ultraviolet data. The model may not be correct, because strong line blocking in the ultraviolet may be important (Underhill, 1973) but has not been included in the model opacities.

The present results argue against the presence of additional line blanketing $>0\overset{m}{.}1$. The measured flux agrees with the predictions of the model to ± 10%. The results of Bless *et al.* show only ± 5% scatter at a value 20% below the model and show no systematic slope. If the synchrotron calibration could be shown to be too low by a constant factor of 0.8, the data of Bless *et al.* would be in good agreement with the flux predicted by the model atmosphere of Klinglesmith down to 1370 Å.

V. CRITIQUE AND ERROR ANALYSIS

The ultimate accuracy of the absolute calibration method used is limited by the accuracy of the NBS standards. NBS claims a maximum uncertainty of 6% at 2250 Å decreasing to 3% at 3000 Å for lamp Q,17. Quoted errors for diode 141 are 6 to 10%. The transfer of the calibration introduces additional uncertainties, while repeated reproducibility checks and the use of more than one standard, for example, lamp EPUV 119, tend to increase confidence and decrease, the error bars. In general, errors fall into two categories: *random errors* associated with the statistics and reproducibility the data and *systematic errors* that are difficult to detect by may change the shape of the calibration.

Random errors for the tungsten calibration are between 5 and 10%. The height of the bump between 2900 and 3250 Å in Fig. 5 is near the limit of the error bar, and the reality of this feature can be questioned. The measured flux is 9% above the model at 3050 Å. The calibrations from the two tungsten lamps have a mean difference of 3% in this range. The UVS recorded 11000 counts between 2900 and 3250 Å during the 22 scans of η UMa, so that a 3 σ statistical fluxuation in the flight data is about 3%. The combination of the 3% error quoted by NBS, the 3% scatter in the calibration data, and the 3% statistics of the flight data could combine to explain the 9% difference between the data and the model. A possible systematic error would be an air absorption feature over the 73 m calibration path having the same shape as the observed bump. These possibilities seem unlikely, and the difference may be real, particularly since the curve of Underhill (1973) and Evans (1972) has a similar shape.

Random errors in the vacuum calibration are dominated by the probable error in the NBS calibration, transfer errors to the flight spectrometer, and reproducibility of the calibration data in Fig. 2. The net probable error is about ± 15%. The additional error from the counting statistics of the flight data can be estimated from the scatter of the data points in Fig. 4 but is generally only a few per cent when a broad band of 50 to 100 Å is considered. A discussion follows of some possible systematic errors in the vacuum calibration with an explanation of why the one we have checked are not important.

1) NBS Photodiode

On 30 November 1972 NBS diode 118 was compared with standard PMT 542-F # 3 of the University of Wisconsin Space Astronomy Laboratory. The PMT was calibrated by T. Fairchild on the Wisconsin synchrotron. The results were interpreted as a calibration of our diode and are compared to the NBS calibration in Fig. 6. The Wisconsin calibration of diode 118 at 1216 and 1608 Å agreed to ± 2% with the January 1972 calibration by NBS, because the diode has a uniform cathode at those wavelengths. The recalibration of diode 118 by diode 141, using the same geometry as in the comparison with Wisconsin, also agrees which the Wisconsin value at 1608 to 2% and within 8% at 1800 and 2000 Å. We feel that the final calibration of diode 118 shown in Fig. 6 is correct from 1700 to 2400 Å to nearly the same accuracy as quoted by NBS (± 6 to 10%) for diode 141.

2) Standard PMT

Diode 118 was used to calibrate our standard PMT before and after the flight using the method described in Section III(c -1). A wavelength independent change in the GQ value by a factor of 1.6 was observed. The post-flight calibration was chosen for the final calibration in Fig. 2 because of the better agreement with the tungsten calibration at 2262 and 2363 Å.

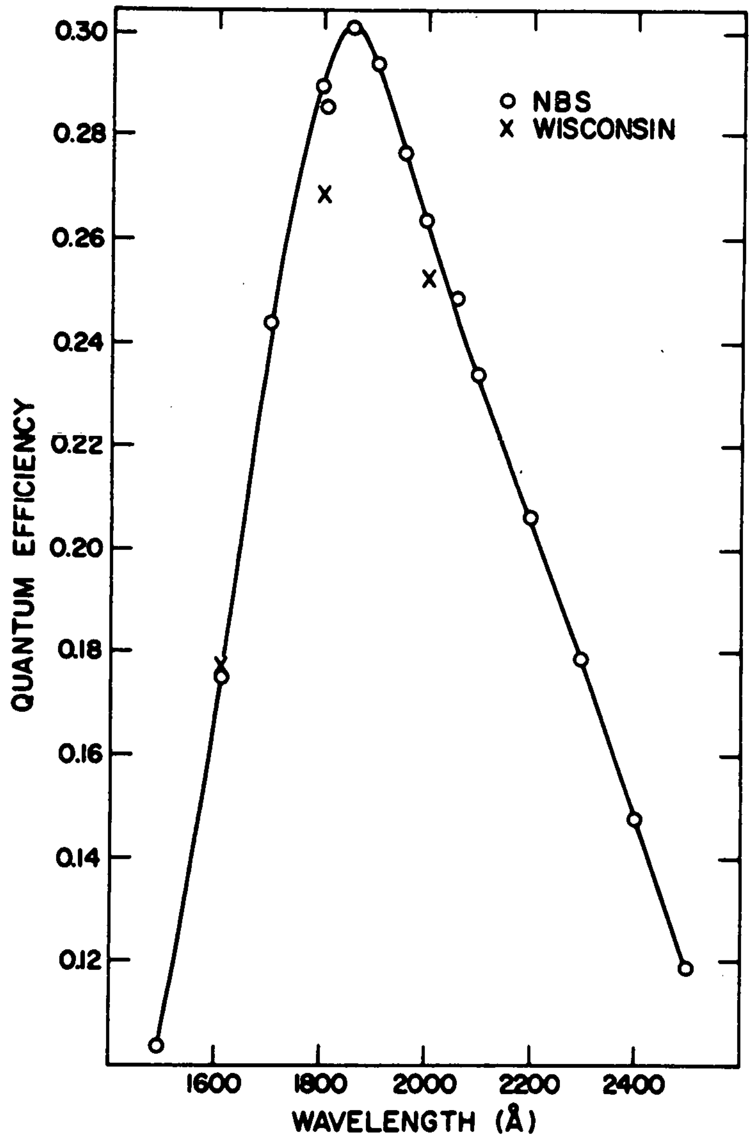

Fig. 6.- The calibration of NBS photodiode 118 by NBS diode 141 (circles). The solid line is the adopted calibration used to derive the flux for η UMa. The crosses are the calibration of diode 118 for the same cathode area derived from the comparison with a standard PMT calibrated by T. Fairchild on the Wisconsin synchrotron.

The *shape* of the calibration in the 1700-2350 Å region is the same for both calibrations of the standard PMT. Apparently, the standard PMT has a gain change and then stabilized immediately after the preflight calibration, because all of the calibration data obtained after that time and displayed in Fig. 2 are self-consistent. A standard PMT equipped with pulse counting electronics having a wide dynamic range should eliminate the uncertainties of spontaneous gain changes. Since the vacuum calibration was normalized to the tungsten calibration, any constant multiplicative errors do not affect the stellar flux measurements.

3) Collimation of the Vacuum Beam

The divergence of the vacuum beam scanned was 6.5, for perfect optics. Aberrations or defocussing in the collimating mirror or UVS could cause a loss of light at the entrance aperture, making S^{-1} and the observed flux too large. Any error should be independent of wavelength, since all of the optical elements were front surface reflectors. Again, the *shape* of the calibration would not be affected by this potential problem. The pre-monochromator slit height could be varied in future calibrations to establish a quantitative limit to this possible error. The most likely cause for the factor of 0.88 necessary to normalize the vacuum calibration to the tungsten calibration is this loss of light at the entrance aperture.

4) Polarization

Gratings may exhibit polarization characteristics that vary with wavelength. Since the collimated beam from the McPherson may be polarized, and the UVS could have a polarized response, a possible systematic error could exist shortward of 2300 Å. A test for the presence of polarization effects would be to calibrate the UVS at a 90° rotation about the beam axis.

5) Scattered Light

Stray light, scattered from gratings and optical surfaces, is a potential source of error at each stage of the calibration. As standard procedure, the scattered light below the detector cutoff was measured and subtracted from the data as a dark count. During the transfer to the standard PMT, any error would be minimized because the diode and PMT have similar responses over most of their sensitive range. In the transfer to the flight spectrometer, any non-monochromatic components of the illuminating beam would be dispersed and detected at other wavelengths in the scan. An upper limit of 3% can be set on the error caused by scattered light at this stage. Scattered light from the flight grating is also unlikely to introduce serious errors. Scattering over several hundred Angstroms would be subtracted as background noise and light scattered by less than one slit width is automatically compensated by the calibration methods.

6) Temperature

The quantum efficiency of photomultiplier tubes may be a function of temperature. Therefore, any change in sensitivity of the flight tubes with temperature should be determined and compared with inflight monitors of the temperature.

VI. CONCLUSIONS

Results from the flight of Aerobee 13.004 support the basic assumptions involved in deriving a stellar atmosphere for a star near an effective temperature of 18000°K down to a wavelength of 1700 Å. The probable errors do not allow agreement with the other observations shown in Figs. 4 and 5.

Future payloads of rockets for stellar calibration purposes should be calibrated by different laboratories before flight, since the current disagreement in ultraviolet measurements probably arises largely from laboratory procedures rather from faulty flight data. A convenient method for intercomparison of laboratory standards might be to fly a scanning spectrometer with a piggyback payload of two or three photometers of the type flown by Bless *et al.* (1972). The photometers could be detached, calibrated at different laboratories, and then reattached for calibration while viewing the same sources as the spectrometer. The cause of any difference between the photometry and the detailed spectrometer scans during a stellar observation should be easy to determine.

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