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ULTRAVIOLET DAYGLOW AND STELLAR BRIGHTNESS MEASUREMENT FROM THE X-15 AIRCRAFT

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Prepared by
UNIVERSITY OF WISCONSIN
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for

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I. Introduction

In 1959 A.D. Code and T.E. Houck proposed to NASA that the Space Astronomy Laboratory undertake a program of astronomical photography from the X-15 aircraft. The purpose of this program was to obtain measurements of stellar brightness in the spectral region between 1800 and 3200 angstroms, which cannot be observed from the ground, but is accessible at moderate heights, above the ozone layer. In preparation for the photographic program, M.S. Burkhead measured the brightness of the daytime sky up to 350,000 feet with a two-channel photoelectric photometer mounted in a fairing behind the pilot's compartment on the X-15. One channel recorded the visible region of the spectrum, while the second channel measured the sky brightness in a region approximately 600 A wide, centered at λ2500. A Nortronics Corporation report (Clark and Muldoon, 1963) describes the data from the visual channel. Analysis of the ultraviolet data forms part of Burkhead's doctoral thesis (1964) and has not been otherwise published.

Test flights with the cameras began in 1965, and at the same time a spectrograph was added in an attempt to obtain photographic spectra of the ultraviolet dayglow. This attempt was unsuccessful and the spectrograph was converted to a photoelectric scanning spectrometer with higher sensitivity. A long rainy season at Edwards AFB delayed the program until the summer of 1966, when four stars were photographed on two flights made August 3 and August 12. I have determined stellar brightnesses at an effective wavelength of 2500 A for three of these stars, α Aurigae, η Aurigae and ρ Aurigae. In addition, the two August flights provide both photographic and photoelectric measurements of the sky brightness.

Section II of this report describes Burkhead's 1963 observations and summarizes his results. Section III presents the results of the stellar photographic program, and Section IV deals with the 1966 measurements of the dayglow.

II. Photoelectric Filter Photometry of the Day Sky

A.D. Code and W. Reining designed the photometer, which is shown in Figure 1. The photometer has an aperture of 4.1 cm^2 and a field of view of 4.7×10^{-3} steradians. All optics are Suprasil quartz. A folding mirror located outside the fairing on the X-15 reflected sky light into the objective lens of the photometer (see Figures 2 and 3), and an interference filter reflected part of the beam into a 1P28 photomultiplier tube. This detector provided the visual data for the Nortronics Corporation. The remainder of the beam passed through the filter and onto the CsTe cathode of an ASCOP 541F "solar blind" phototube with a LiF window. The relative sensitivity of the ultraviolet channel is shown in Figure 4.

This photometer was carried to a peak altitude of 273,000 feet on January 17, 1963 and later, on August 22, to 352,000 feet. During each flight the line of sight of the photometer moved around the sky as the attitude of the X-15 changed. The dashed lines in Figures 5 and 6 follow the motion of the photometer pointing in time. In both cases, launch occurred at 126 seconds.

Burkhead determined the absolute sensitivity of the photometer with a NBS standard lamp. The sky intensity (ergs cm^{-2} sec^{-1} $ster^{-1}$) observed at various heights is shown in Figure 7. He describes these data as follows:

"A sudden increase in brightness above 35 km is due to the reduction in the ozone concentration. It is above the altitude of this knee that the true ultraviolet sky is seen. Most of the radiation observed below this altitude is radiation longward of 3000 A.

"After the peak altitude had been reached on the August 22 flight, the ultraviolet channel saturated until the aircraft re-entered the ozone layer. During this time the visual channel exhibited two peaks. Since the photometer worked perfectly on the ground both before and after the flight, and since the data agree well with data of the other flight and the upward leg of this flight, the saturated position is not likely to be due to malfunction of the photometer. There is the definite possibility that even though the photometer is looking some 40° from the sun, solar radiation is being scattered off the mirror or mirror housing into the photometer. The line of sight at the first peak is the nearest position to the sun. The second peak is also near the sun, although there is a clustering of points about this position.

"Another possibility is that the photometer actually saw a 'cloud'. Noctilucent clouds are observed at an altitude of 250,000 ft."

Burkhead also notes that ". . . below the photometer and toward the tail is the Auxiliary Power Unit (APU) exhaust. Through this exhaust come the waste products of the burned hydrogen peroxide gas that controls the aircraft's power systems. With the photometer looking some 63° above this exhaust no contamination of the observations is expected. Some contamination could possibly occur, however, from the reaction controls mounted in the nose of the aircraft."

To investigate the origin of the observed sky intensity, Burkhead first computed the expected Rayleigh scattering of sunlight in the passband of the photometer. When this proved inadequate to explain the observations he concluded that an emitting layer probably existed above the X-15 and the most likely source of the emission was fluorescence of the O_2 molecule in the Schumann-Runge bands. Assuming as a first approximation that all solar intensity in the Schumann-Runge bands is absorbed (since the atmosphere is opaque to this radiation below 30 km) and that the absorption occurs from the ground state of the molecule, he computed the fluorescence spectrum shown in Figure 8. The values of the ordinate correspond to solar illumination over 4π steradians, so that the actual emission is the ordinate value multiplied by 5.42×10^{-6}.

The sum of Rayleigh scattering and O_2 fluorescence in the photometer passband computed on the assumptions above is shown in Figure 7. Burkhead then modifies this curve: "Between 40 and 85 km the production of atomic oxygen increases by approximately a factor of ten . . . If the assumption is made that absorption of solar radiation by the Schumann-Runge bands increases by the same factor between 85 and 40 km, then the agreement between theory and the X-15 flight data is good."

The results of Sections III and IV revise Burkhead's sky brightness downward by roughly a factor of ten at 75 km. The smaller value agrees well with Tohmatsu's (1963) more detailed treatment of the energy re-emitted in the fluorescence process and points up the difficulty of measuring low intensities in the presence of sunlight.

III. Ultraviolet Stellar Photography

A. Instrumentation and Operation

Four Nikon 35 mm camera bodies with motor-driven film transport mechanisms were equipped with Suprasil quartz optics designed and built by Barnes Engineering Company. The optics consist of a lens system in a barrel mount and a field flattener located immediately above the focal-plane shutter. The focal length of the lens is 108 mm. An interference filter mounted in front of the lens is the limiting aperture, producing an f/5 system. Eastman 103-O UV film was used on all flights.

A gyroscopic platform built by Astronautics Corporation of America supported the four cameras in a hatch behind the pilot's compartment. The platform was designed to provide a constant pointing direction within an rms fluctuation of one minute of arc. The camera optics were designed to the same resolution. Camera aiming depended on the pilot. SAL provided aircraft attitude coordinates, which were radioed to the pilot immediately before launch. When the pilot achieved the desired attitude near the peak of his trajectory, he threw a switch that opened the hatch doors and began a timed sequence of exposures. During this sequence the initial attitude had to be maintained within about 10° to avoid obscuring the field of view (in the roll direction) or hitting platform limit stops (in the pitch direction). The hatch doors closed and the platform returned to the caged position automatically at the end of the sequence unless the pilot previously overrode the timer manually.

Any attempt to measure stellar brightness in the daytime must avoid contamination by sunlight scattered within the instruments or from their supporting structure. The original design of the gyroscopic platform and camera support included the X-15 inself as a sun shield. With the high peak altitude anticipated for the X-15, the pilot would have sufficient time before re-entry to reach star fields farther than 90° from the sun. With ship X-15A-2, which was modified during installation of the instrument hatch, FRC limited peak altitude to 250,000 feet and deviations from normal flight attitude to $\pm 5°$ in pitch and $\pm 20°$ in roll. Even at the earliest permissible launch times, sunlight would illuminate part of the hatch. As a result the camera support had to be lowered as much as possible to provide maximum space for light shields within the confines of the hatch. Figure 9 shows the three light shields used on the flights of August 1966. The two larger shields are shown clamped in their normal positions on the ultraviolet lens barrels. Since the modified camera support left space for only two u.v. lenses with their shields, two of the cameras were used with the standard Nikon lenses for photography in the visual. The smallest shield fits one of the visual cameras.

B. Data and Results

Four stars have been identified on ultraviolet films taken on two flights.

STAR	SP.	V	DATE	LAUNCH TIME	ALTITUDE
η Aur	B3 V	3.17	1966 Aug. 3	0845 PDT	248,000 ft.
ρ Aur	B5 V	5.09	1966 Aug. 3	0845 PDT	248,000 ft.
α Aur	G III F III	0.05	1966 Aug. 3	0845 PDT	248,000 ft.
α Gem	A + A	1.97	1966 Aug. 12	1028 PDT	230,000 ft.

(V is the visual magnitude)

The exposure sequence began approximately 2 minutes after launch and lasted 30 seconds. The August 3 flight carried two u.v. cameras and two visual cameras; for the August 12 flight one of the visual cameras was removed to provide space for the sky spectrometer. On both flights, essentially identical interference filters were mounted on both cameras. The filters have a peak transmission of 30 percent at λ2500 and a width at half-maximum of approximately 500 A.

Only one film appears to be free of scattered sunlight. α Aur, η Aur, and ρ Aur have been identified on two frames of this film. The exposure times were 20 seconds and 5.4 seconds for these frames. Two frames from the August 12 flight show α Gem, but these frames are badly light-struck. No stellar images have been found on the visual films, which were also strongly affected by sunlight.

Figure 10 shows part of the 20 second frame of August 3. η Aur is the brightest image, in the upper left. Near the center is ρ Aur, and α Aur is very close to the frame edge at the bottom of the figure. The images have a "wishbone" shape indicating excursions of the gyro platform up to several minutes of arc. (The white streaks on either side of the images are ink marks on the film.) The 5 second images are smaller and more nearly straight lines.

On previous flights, the FRC flight records showed that the platform performed to specifications unless the pilot accelerated rapidly in roll or pitch as he attempted to hold position. Maneuvering violent enough to disturb the platform was common at zenith angles of 20°, and in anticipation of such pointings we decided to increase the gain in the servo loops. As it turned out, both August flights were launched as planned, and the pilot acquired and held the near-zenith pointings smoothly. The excursions in the images are apparently the result of the decreased damping in the gyro.

The u.v. films were returned to SAL in their flight cassettes and calibrated there. A hydrogen lamp, monochromator, and concave mirror were used to produce a uniform, collimated beam at the central wavelength of the passband. The spectral purity of the calibration beam was 135 A. The intensity of the beam was measured with a photomultiplier tube that was in turn compared with a NBS standard lamp and a Penray source (Childs, 1962). One of the u.v. cameras, complete except for its interference filter, was placed in the calibration beam and a series of exposures made at different intensity levels and exposure times. The transmission of the camera optics is essentially flat across the filter passband. Only the transmission curve of the filter and variation in film sensitivity are required to obtain absolute stellar brightness, and both quantities were measured.

Both the stellar images and calibration (monochromator slit) images were enlarged 17.6 times onto medium-contrast slide plates. Density profiles of the enlarged stellar images were made 0.5 mm apart with a 0.5 mm analyzing slit. Although different parts of the image were formed with different exposure times, the total energy in the image can be determined from the density profiles if film reciprocity holds. Since the calibration images made with exposure times between 2 seconds and 18 seconds do not show any evidence of reciprocity failure, the assumption of reciprocity in the stellar images is a reasonable one. Another source of error is the Eberhard effect. The main segments of the 20^s stellar images have nearly the same width as the calibration images, about 0.16 mm. Eberhard effect is probably responsible for discrepancies in the 5^s images, which are narrower.

Given in the table on the next page are the measured λ2500 filter brightnesses of ρ and α relative to η Aur, expressed in magnitudes, the difference in visual magnitude (on the UBV system), and the magnitude difference expected on the basis of recent model atmosphere calculations. These values are taken from the 20^s frame.

	ΔM_{2500}	ΔV	ΔM_{2500} (Model)
ρ/η	2.25	1.9	2.3
α/η	2.0	-3.1	1.5

The models used for ρ and η (Strom and Avrett, 1965) are unblanketed models with effective temperatures of 16000° and 19000° K. According to the new temperature scale of Morton and Adams (1967, in press), the effective temperatures of blanketed models for B5V and B3V stars are, resp., 15,000° and 18,000°, but unblanketed models with 1000° higher temperature predict the same visual and near u.v. fluxes. There are no models available for α Aur. The components of this spectroscopic binary are uncertainly typed as G and F giants (Franklin, 1959). For purposes of comparison I have listed the magnitude difference expected if the energy distribution in α Aur were the same as the sun's.

Next we determine the absolute brightness of η Aur at λ2500. Figure 11 shows the measured response curve of the film plus filter, relative to the no-filter response of the camera at λ2500. Also plotted is the relative flux per unit wavelength taken from Strom and Avrett's (1965) model with T eff. = 19000° K. Thus the filter effectively transmits 12.4 per cent of the flux of a B3V star in the region 2000 - 3400 A. The two absolute determinations of the calibration beam intensity agreed to 30 per cent.

Taking the mean value for the beam intensity gives a value of

$$2.66 \times 10^{-7} \text{ ergs cm}^{-2} \text{ sec}^{-1}$$

for η Aur as seen through the filter, or

$$2.14 \times 10^{-6} \text{ ergs cm}^{-2} \text{ sec}^{-1}$$

in the region 2000 - 3400 A. This corresponds to a flux of

$$1.60 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ A}^{-1} \text{ at } \lambda 2500.$$

From the known solar energy distribution, the V magnitudes of the sun and η Aur, and Strom and Avrett's model used above, the predicted flux from η Aur at the top of the atmosphere is

$$1.32 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ A}^{-1} \text{ at } \lambda 2500.$$

Stellar fluxes derived from the 5^s frame give a magnitude difference of 2.2 between η and α, in good agreement with the 20^s frame. However, the absolute fluxes are about 25 percent larger. Because the stellar images on the 20^s frame more nearly duplicate the calibration images, I am inclined to give the 20^s frame higher weight. The 5^s image of ρ Aur is visible on the film, but too weak to separate accurately from the sky background.

IV. August 1966 Measures of the Sky Brightness

Both the 20^s and 5^s frames from the flight of August 3 (75 km altitude) give a sky brightness at the zenith of

$$0.034 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$$

before correction for the filter transmission. If the spectrum is flat, this corresponds to

$$0.28 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ in the region 2000 - 3400,}$$

or $$2.0 \times 10^{-4} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ A}^{-1},$$

substantially less than Burkhead's results.

The August 12 flight carried a scanning spectrometer, which was designed to fit into the hollow gimbal, whose axis projects vertically through the center of the square camera array. Figure 12 shows the spectrometer with its associated power supply, amplifiers, and motor-drive switching relays. Light enters the spectrometer through the 5 mm hole in the cover plate, passes through a slit located 4.5 cm beneath, and illuminates a concave mirror near the bottom of the brass portion of the spectrometer casing. The mirror sends a converging beam to a plane diffraction grating, which forms the spectrum in the space adjacent to the mirror. According to the theory of convergent-beam gratings (Gillieson, 1949) the spectrum is astigmatic with a curved focal surface. The 1200 line/mm grating (made by Diffraction Products) is used here at normal diffraction and produces a dispersion of 84 A/mm. A 12 volt Globe motor moves an RCA C70129C (a miniaturized 1P21 with a sapphire window) through the mean focal plane and covers the region 3200 - 2100 A in 7 seconds. A small aluminized flat attached as a lip to the phototube deflects the spectrum onto the cathode. See Figure 13. In the right-hand photograph the phototube and mirror flat are seen reflected in the grating on the right side of the spectrometer casing. (The window of the phototube is covered with tape.) At the end of each scan, microswitches reverse the direction of the scan and step the input in turn to three current amplifiers. One amplifier is conventional, with an input impedance of 10^9 ohms. The other two are field-effect transistor amplifiers with 10^8 and 10^9 ohms. Field-effect transistors of the type used on the August 12 flight are very sensitive to external fields, and the 10^8 amplifier failed sometime before the hatch opened, when the scanning cycle begins. The 10^9 FET operated satisfactorily during the flight but did not work on its return to SAL. Possibly corona discharge across the 700 volt supply to the phototube was responsible for at least one failure.

Prior to August 12, the spectrometer was flown as a spectrograph. To the right in both photographs of Figure 13 is a 35 mm film holder that replaces the aluminum spectrometer cap for photographic work. With this holder attached, half of the film strip lies behind the mirror support and can be rotated into position for a second (usually calibration) exposure with the knob. The fact that no sky spectra were obtained with the spectrograph gives an upper limit to the sky brightness of approximately 1.2×10^{-2} ergs cm^{-2} sec^{-1} per 40 A.

The peak altitude of the August 12 flight was 70 km. Three 100 A resolution scans with the 10^9 FET amplifier show a slight rise in the level between 3200 and 2400, with the peak near 2900. The signal is barely detectable, but it is the same on all three scans and the spectral shape is not characteristic of scattered sunlight. The intensity averaged over the 800 A region where the signal is detectable yields

$$0.09 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ or about}$$
$$1 \times 10^{-4} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ A}^{-1},$$

which is about half of the photographic measurement in half the wavelength interval.

The photographic value of 0.03 ergs cm^{-2} sec^{-1} $ster^{-1}$ appears to be a good upper limit to the zenith brightness of the daytime sky at 75 km as seen with the response curve of Figure 11. The apparent magnitude of a B3V star whose brightness in one square minute of arc equals the sky brightness, when this response is used, is +8.0.

Tohmatsu (1963) has computed the Schumann-Runge dayglow and Rayleigh scattering integrated over the region 2000 to 3000 A. He predicts an intensity at 75 km of

$$0.15 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$$

For the same interval and with the Schumann-Runge spectrum of Figure 8, the X-15 data imply a measured intensity of

$$0.23 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1},$$

in good agreement with Tohmatsu's model.

Since its inception the X-15 program has called on the talents of every member of the Space Astronomy Laboratory and many people elsewhere.

It is a pleasure to acknowledge, in addition to those mentioned in this report, the contributions of R. C. Bless, J. F. McNall, and D. J. Schroeder of SAL, R. Voith of ACA, and Lovic Thomas at FRC. I want especially to thank James Love for his hospitality at FRC and for his willingness to meet the demands of a sometimes trying project. This work was performed under NASA Contract NASw-66 and Grant NsG-618.

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Strom, S. and Avrett, E. 1965 Ap. J. Supp. 12, 1.

Tohmatsu, T. 1963, Report of Ionospheric and Space Research in Japan 17, 187.

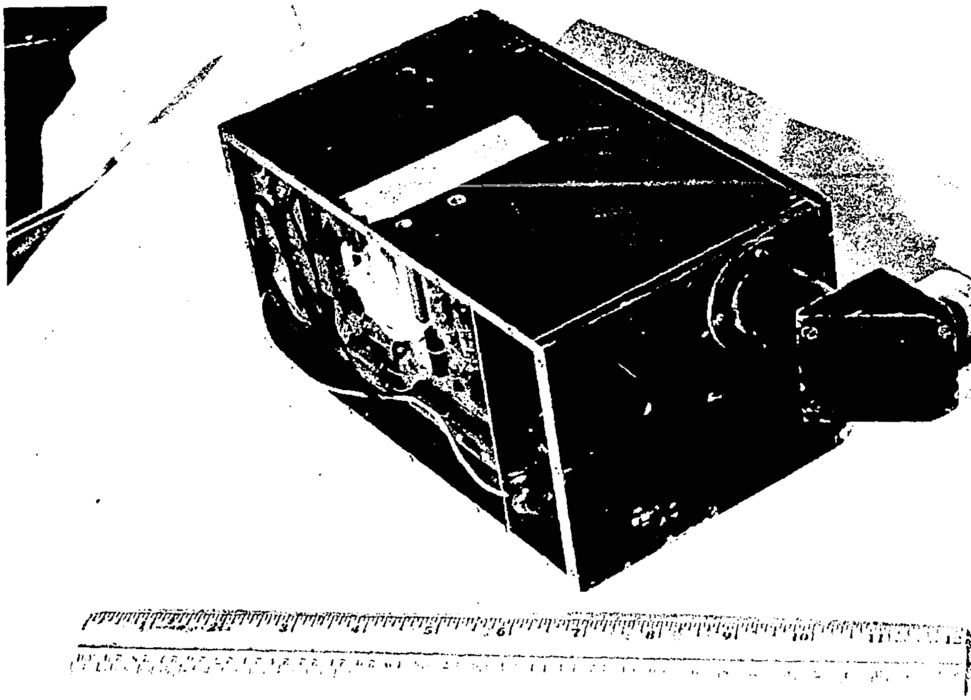

Fig. 1. X-15 two-channel photometer.

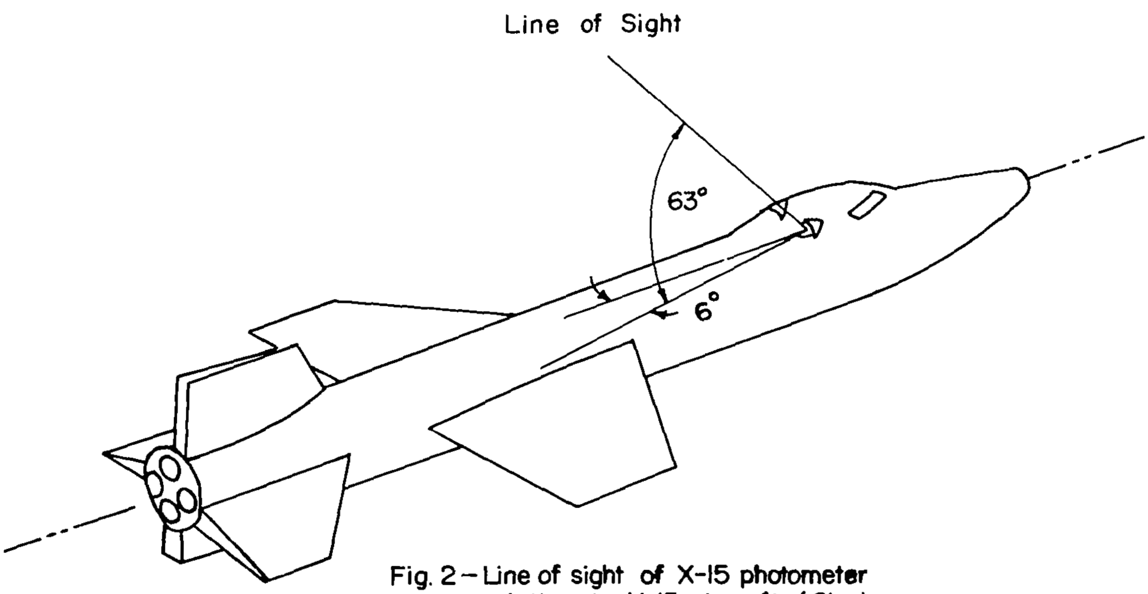

Fig. 2 — Line of sight of X-15 photometer relative to X-15 aircraft. (Clark and Muldoon 1963)

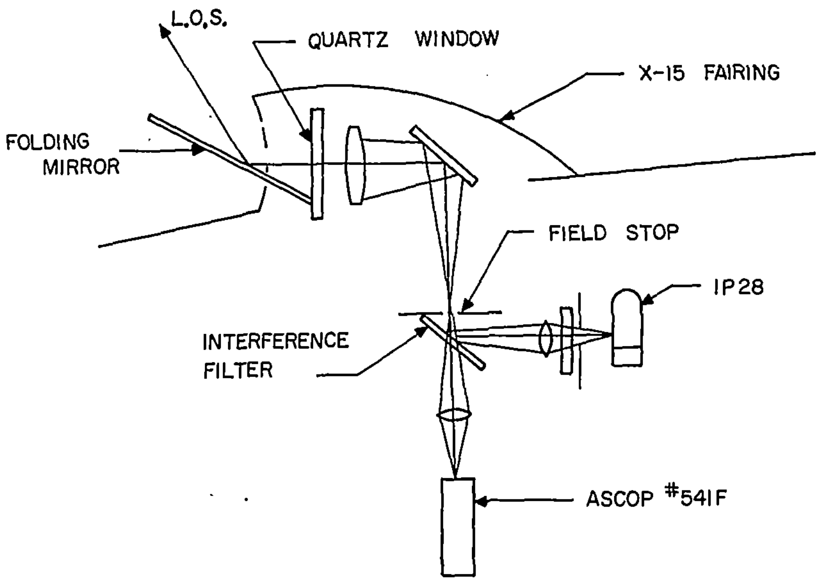

Fig.3 X-15 Two-channel photometer. (Clark and Muldoon 1963)

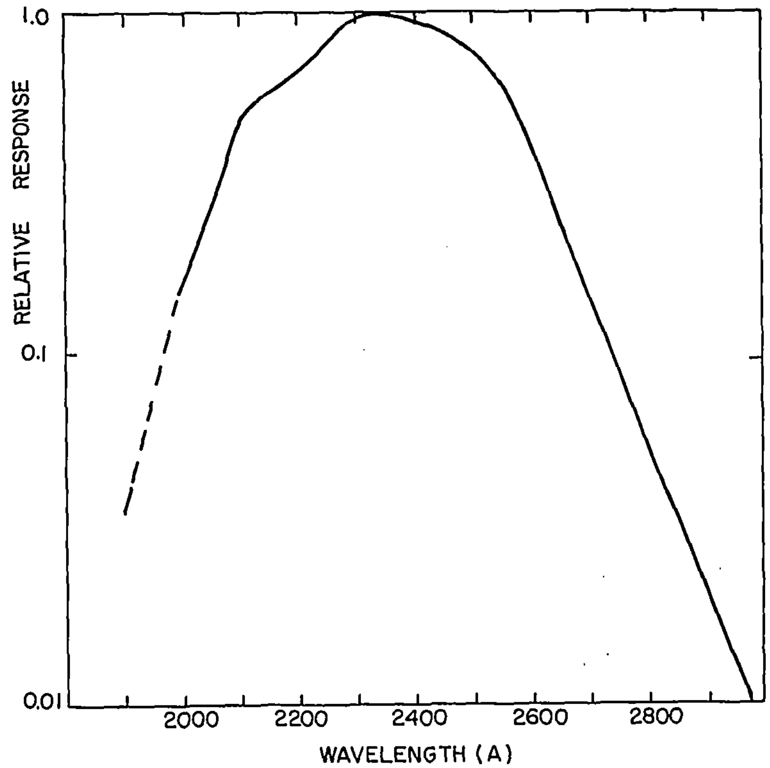

Fig. 4. Sensitivity of X-15 photometer to radiation of constant energy.

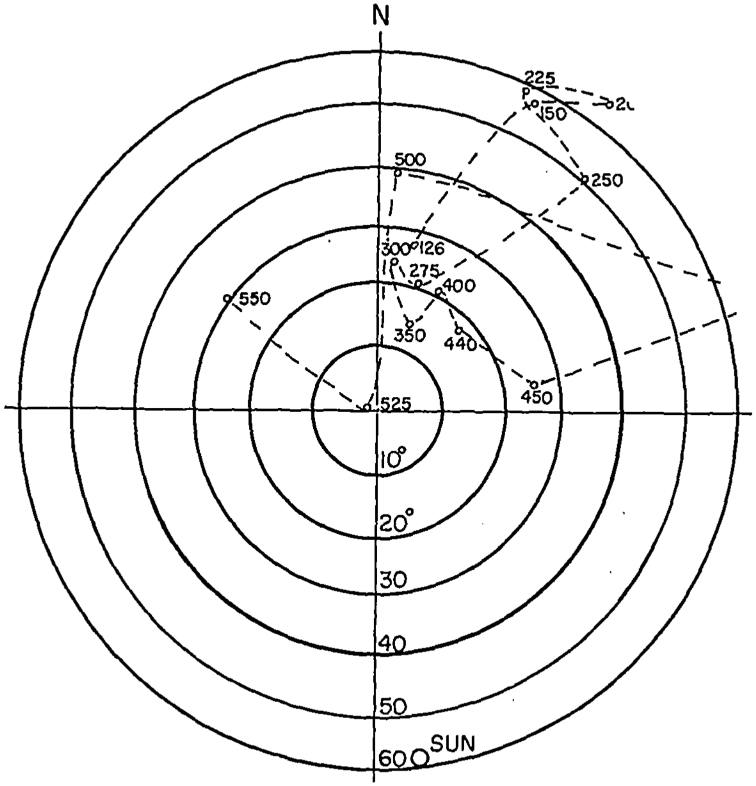

Fig. 5 Projection of the line of sight of the X-15 photometer on the sky. Flight of January 17, 1963.

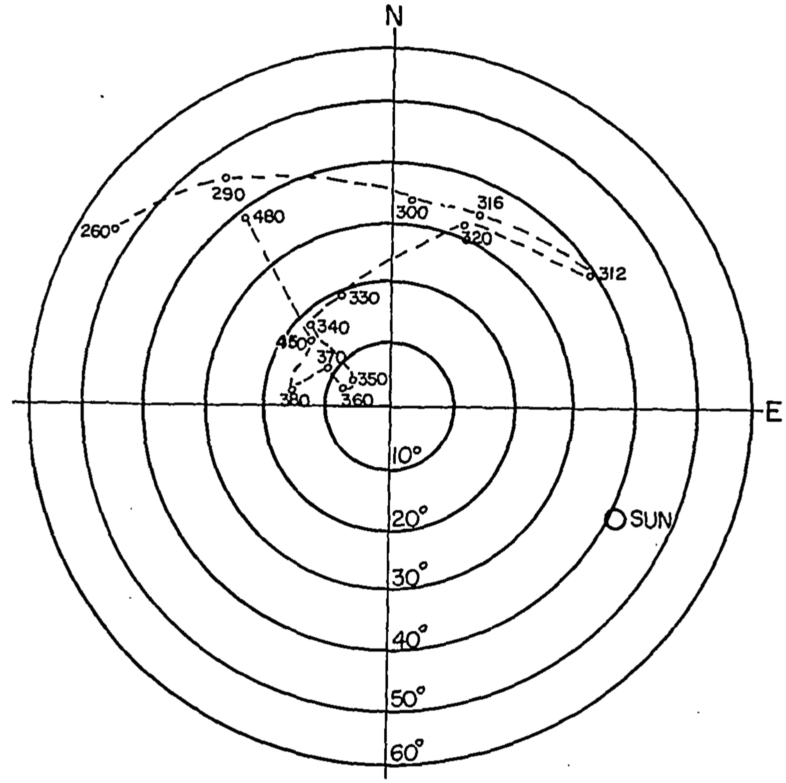

Fig. 6 Projection of the line of sight of the X-15 photometer on the sky. Flight of August 22, 1963.

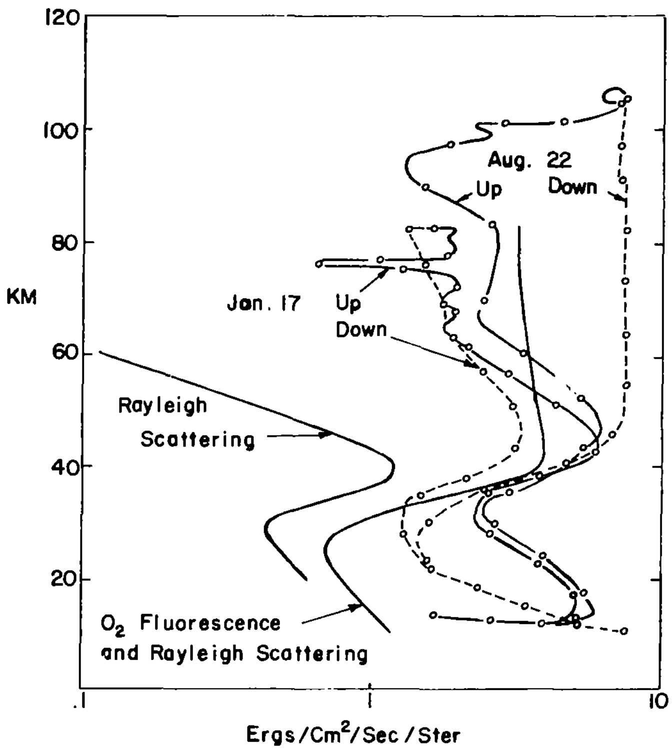

Fig. 7 Reduced X-15 flight data and results of computations.

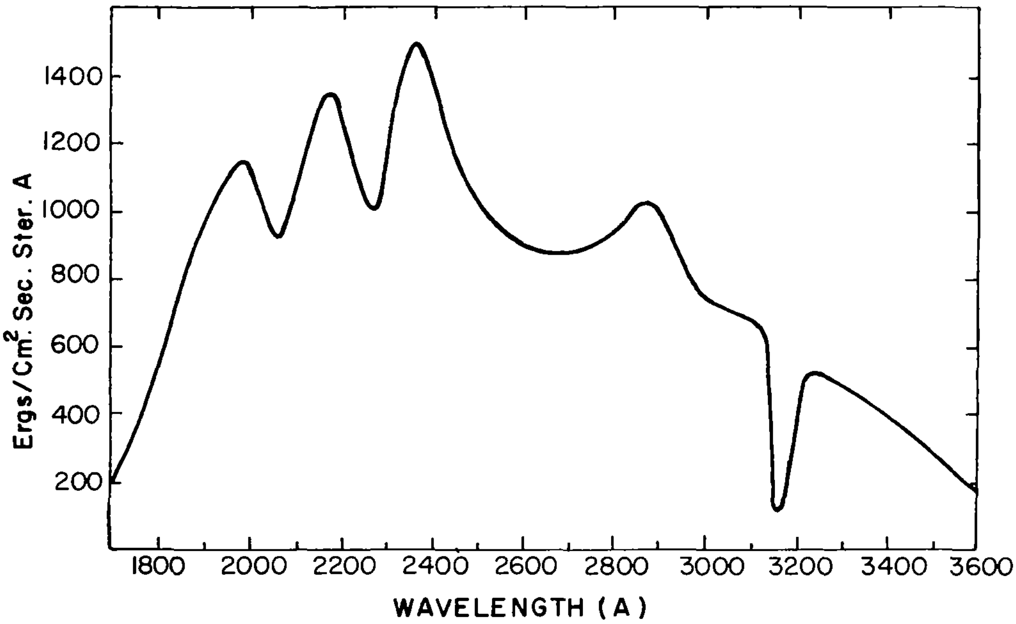

Fig. 8 Calculated Schumann-Runge emission spectrum.

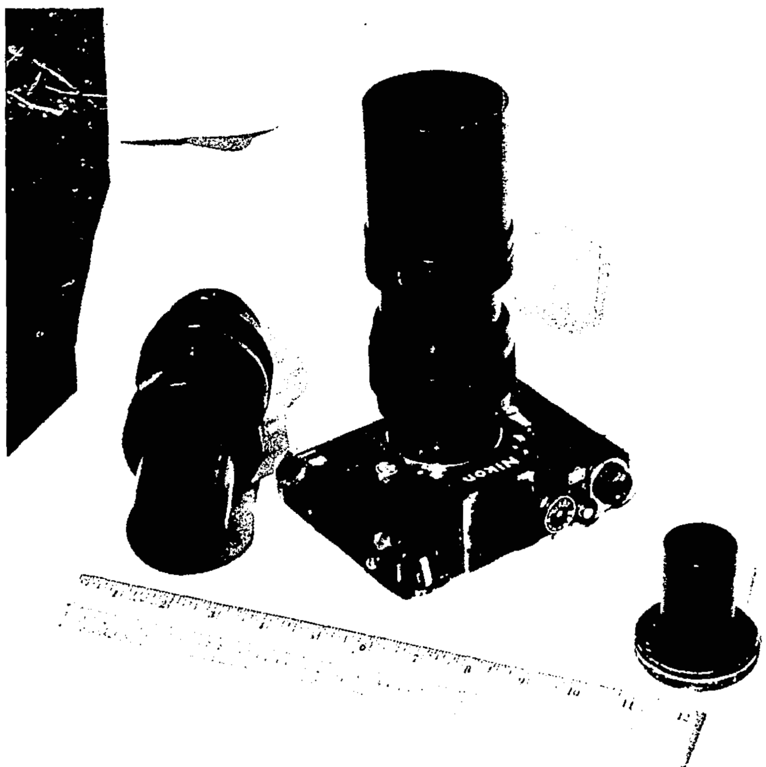

Fig. 9. Center: complete u.v. camera. Left: u.v. lens barrel with sun shield. Right: sun shield for visual lens.

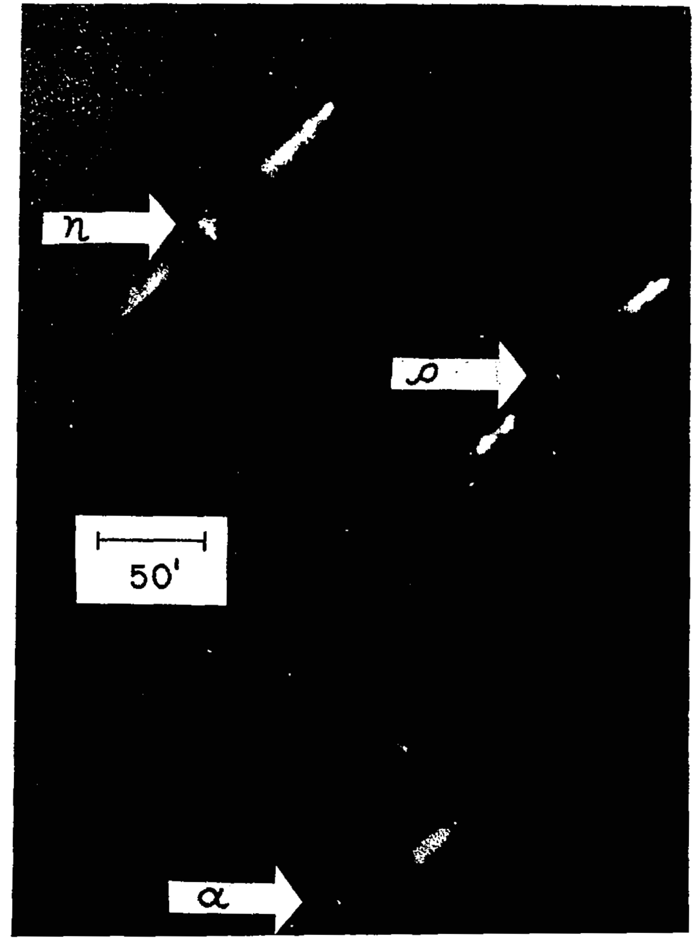

Fig. 10. Part of 20-second frame from flight of Aug. 3, 1966. (see text)

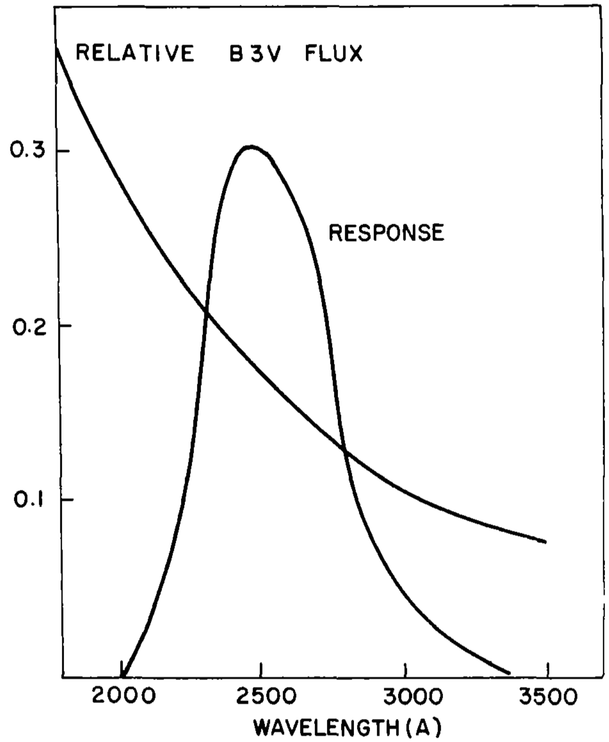

Fig. 11. Relative stellar flux and instrument response.

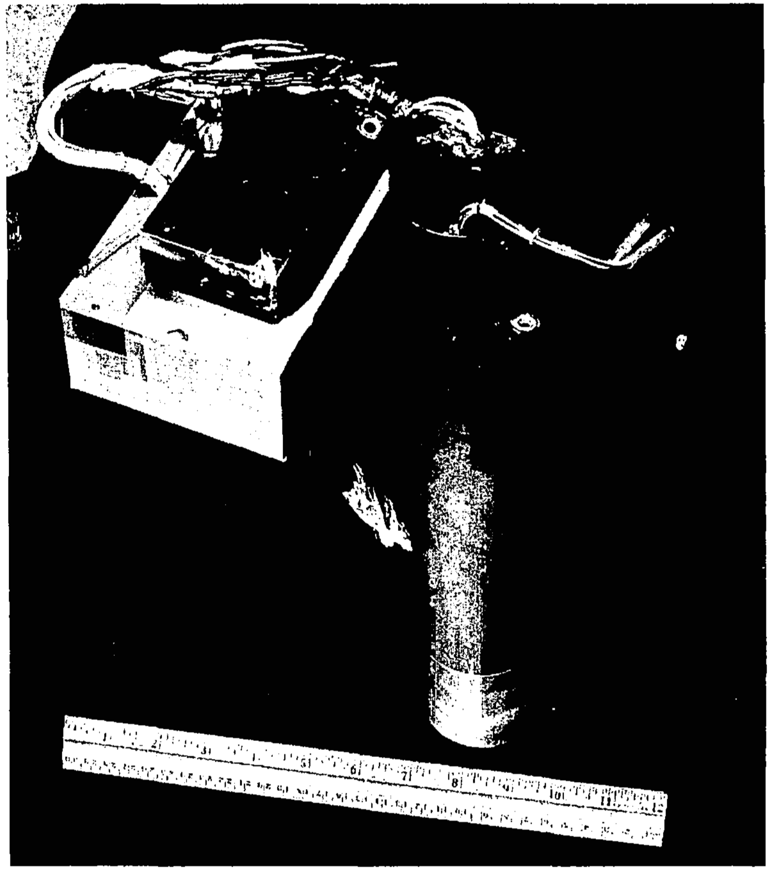

Fig. 12. Photoelectric scanning spectrometer.

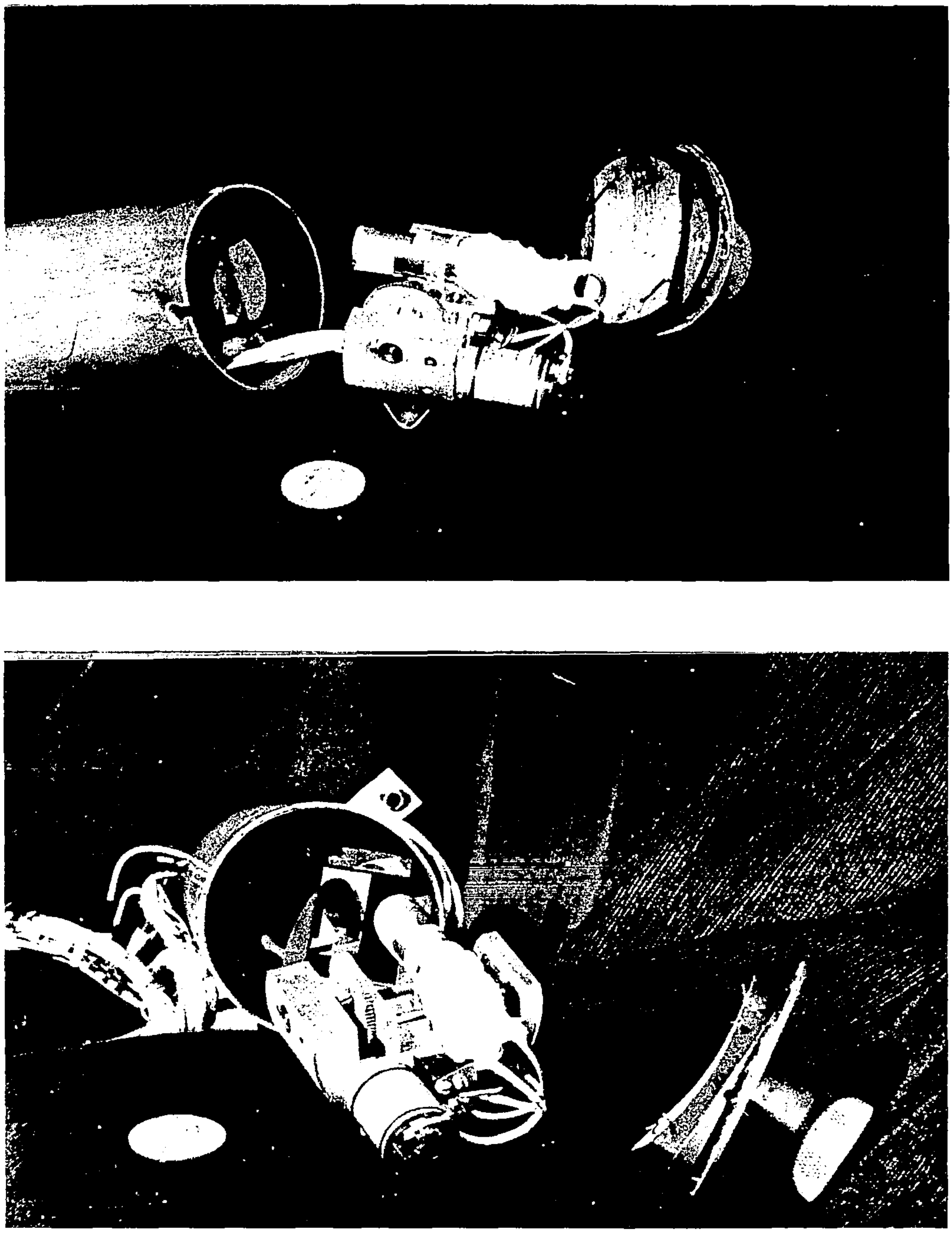

Fig. 13. Spectrometer drive mechanism with miniature photomultiplier. Also shown is the alternate back for photographic spectra.