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ABSOLUTE ULTRAVIOLET SPECTROPHOTOMETRY OF:

αCMa, γ Ori, κOri, and αLeo:

A Continuing Calibration Program and Some Preliminary Results

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GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Spectral observations of the stars αCMa, γOri, κOri, and αLeo have been obtained in the range 1150 to 4000 Angstroms, using rocket borne spectrometers. The payloads have 13-inch diameter telescope, a rotatable concave diffraction grating, and three pulse counting photomultiplier photometers. The laboratory standards used as photometric references derive their primary calibration directly or indirectly from the National Bureau of Standards. An error range of up to $\pm$10 per cent is attributed to these laboratory standards; $\pm$ 8 per cent to the calibration procedure; and $\pm$ 10 per cent is assigned as an accidental error range. The overall RMS precision error range is about $\pm$ 15 per cent. The observations are systematically lower than those of Carruthers (1968) at 1270 Angstroms, of Smith (1967) at 1376 Angstroms, and of Cambell (1970) at 2150 and 2550 Angstroms. The data are also about 15 per cent lower than the ground-based photometry reported by Schild, Peterson, and Oke (1971). Comparison with the provisional calibration of the OAO-II long wavelength scanner shows good agreement longward of 2200 Angstroms. From 2200 to 1800 Angstroms the OAO-II calibration infers flux values systematically higher than the present observations, by amounts up to 30 per cent. The OAO-II short wavelength scanner calibration agrees with the α Leo observations but disagrees for κ Ori and γ Ori.

ABSOLUTE ULTRAVIOLET, SPECTROPHOTOMETRY OF: α CMa, γ Ori, κ Ori, and α Leo: A Continuing Calibration Program and Some Preliminary Results

THE OBSERVATIONS

Three Aerobee sounding rockets with ultraviolet spectrometer payloads have been launched from White Sands Missile Range. The payloads were each intended to measure the ultraviolet fluxes of four stars. The range of spectral observation was from 1150 to 4000 Angstroms.

The first rocket (NASA 4.251) was launched 14 March 1969. Good data were obtained from the observation of α Leo, but that payload was destroyed during re-entry. A second flight (NASA 4.252) was made on 13 December 1969. No observations were completed; however the payload was recovered in excellent condition. Post-flight recalibration showed the senstivity of the instrument to be within 5 per cent of the pre-flight values. The third flight (NASA 13.041) was made 31 October 1971. Recalibration of the spectrometer showed no change in the instrumental sensitivity from pre-flight to post-flight. The observational data available is summarized in Table 1. For flight 13.041 the observing sequence was in the order listed in the table. Repeated scans of γ Ori were made as the rocket changed altitude from 140 to 204 kilometers. Each complete spectral scan required 20 seconds. No spectral variations due to residual atmospheric absorption were detected. Thus, no corrections for atmospheric absorption have been applied to any of the data.

THE PAYLOAD

The payload telescope optics possess a Dall-Kirkham figure with a focal ratio of f/9.7, a clear aperture of 32.8 cm, and a central obscuration of 15.5 cm. The image of the telescope defines the limiting resolution since there is no entrance slit. The entrance slot is about 10 x 15 arc minutes. Behind this slot, the light beam diverges until it strikes a 600 line per millimeter concave diffraction grating of 40.07 cm radius. The dispersed light, approximately collimated, is focussed onto three pulse counting photomultiplier photometers by means of a spherical mirror mounted on the back of the primary mirror support structure. Instantaneous resolution of 10 Angstroms is fixed by the slit placed in front of each photomultiplier. The exit slits, fixed in the spectrometer focal plane, are separated by 750 Angstroms. The grating moves at a constant rate over a spectral interval of 1500 Angstroms and the wavelength values during successive scans alternately increase and decrease. Three EMR photomultipliers were used in each payload. The short wavelength one had a lithium fluoride window with a cesium telluride cathode; the medium wavelength, a sapphire window and a bialkali cathode; and the long wavelength, a 9741 glass window and a bialkali cathode. The photomultipliers were operated in a pulse counting mode with a low level discrimination. The digital output of each was converted to analog rate signals for telemetry to several ground stations. The ground station magnetic tapes were reconverted into digital format and the digital tapes made available for post-flight analysis.

THE CALIBRATION REFERENCES

Each payload was calibrated by placing it in a vacuum chamber where its response to ultraviolet light could be directly compared with that of several laboratory reference photomultipliers. The light source was the exit slit of a one-third meter monochromater placed at the focal point of a Dall-Kirkham collimator. Two photomultipliers, one coated with sodium salicylate, were mounted on an X-Y scanning device which enabled the entire collimated beam to be surveyed. Two laboratory reference photomultipliers were located at fixed positions in the collimated beam, between the X-Y scanner and the flight payload. The scanner monitors were used to determine the relative distribution of light in the beam incident on the payload. The average incident flux was found by comparison of the scanner data with the flux values determined at the fixed monitor locations. Data were discarded when the uniformity of the incident beam varied more than ±10 per cent from its average value.

Prior to the successful conclusion of flight 13.041, the laboratory reference photomultipliers were calibrated at 2537 Angstroms using four Eppley thermopiles. The photomultipliers were also calibrated at 1216 Angstroms using an open window nitric oxide ion chamber. The ion chamber results indicated the same quantum efficiency for sodium salicylate at 1216 and 2537 Angstroms, within about ±5 per cent. However, the ion chamber measurements could not be used to determine absolute sensitivity of the reference photomultipliers because the cathode surfaces could not be uniformly or fully illuminated. Thus, the pre-flight absolute calibrations were based on the 2537 Angstrom comparison with the thermopiles and the assumption that sodium salicylate has a uniform quantum efficiency as a function of wavelength.

Following flight 13.041, four EMR photodiodes calibrated by the National Bureau of Standards have become available for comparison with the laboratory reference photomultipliers. The diodes have magnesium fluoride windows and rubidium telluride cathodes. Direct comparison of the laboratory references and the diodes in the spectral region 2000-2385 Angstroms indicates agreement to within ± 5 per cent of the original thermopile calibration and the assumption about sodium salicylate. The present flux values derived for the stars are dependent on the assumption of uniform quantum efficiency for sodium alicylate below 2000 Angstroms. A preliminary recalibration of the laboratory reference photomultipliers shortward of 2000 Angstroms indicates that the uniform quantum efficiency assumption for sodium salicylate is correct, but this conclusion is based on data from a series of low light level measurements of low precision. Post-flight recalibration is continuing.

The use of sodium salicylate as a relative reference cannot be extended longward of 3400 Angstroms. In the spectral range 2600 to 4000 Angstroms, the relative response of the 13.041 flight payload was determined directly by using the payload to observe the output of three tungsten iodide coiled filament irradiance standard lamps, calibrated by the National Bureau of Standards. In the overlapping range 2600 to 3400 Angstroms, the spectral responses derived by both techniques were the same within ± 5 percent.

The final sensitivity values determined for the 4.251 payload were based on the laboratory reference, calibrated at 2537 Å and extended longward and shortward of that wavelength using sodium salicylate. The final sensitivity values for the 13.041 payload were determined in the same manner, checked in an absolute sense by comparison with diodes calibrated by the National Bureau of Standards in the range 1164 to 2385 Angstroms, and extended longward to 4000 Angstroms by comparison with tungsten irradiance lamps also calibrated by the National Bureau of Standards.

THE CALIBRATION TRANSFER PROCEDURE

The basic problem encountered in the transfer of the calibration from the laboratory reference to the payload is one of dynamic range. The reference photomultipliers must be illuminated intensely enough to provide a strong signal without overloading the payload photomultipliers. This problem was solved by using the "dynamic" technique described below.

The exit slit of the monochromater used as the light source has a dispersion scale of 26.5 Angstroms per millimeter. The image of this slit in the focal plane of the payload is dispersed an additional 53 Angstroms per millimeter by the payload grating. Thus, a monochromater output having a real spectral purity of 26.5 Angstrom could have an apparent bandwidth equivalent to 79.5 Angstroms in the payload focal plane if the monochromater dispersion and the payload dispersion directions were the same, or only 26.5 Angstroms if the dispersion directions were opposed. With a two millimeter exit slit width on the monochromater (the maximum possible), the real spectral width is 53 Angstroms while the maximum apparent width is 159 Angstroms in the payload focal plane. Because the laboratory reference photomultiplier responds to the entire output of the monochromater and the payload responds to only 10 apparent Angstroms at a time, the intensity ratio between the reference and the payload photomultipliers can be increased by up to a factor of 16. At each calibration wavelength four payloads spectrometer scans were recorded on magnetic tape. Data were also recorded from the two photomultipliers on the X-Y scanner, which were kept in a "standard" location and from the two reference photomultipliers. Data points were recorded every 0.081 seconds, corresponding to 6.55 Angstrom intervals at the payload scan rate of 81 Angstroms per second. For the widest slits, twenty four non-zero data points were recorded during each of the four spectral scans. By integrating the response of the payload to this well defined spectral band and comparing it to the signals from the laboratory standard photomultipliers, the calibration was derived. The flight instrument was calibrated at twenty five Angstrom intervals over the entire spectral range from 1150 to 3400 Angstroms. During the course of the calibration, the monochromater exit slits were always kept small enough that the incident spectral purity was small compared to the variations in spectral response of the payload.

The repeatability of the raw data was within ±10 per cent using this calibration procedure. Corrections for non-uniformity of the collimated beam based on X-Y scans of the beam at periodic intervals improved the repeatability to about ± 5 per cent. Based on the stated accuracy of the thermopiles, the repeatability limits, and a comparison of the pre- and post-flight calibrations limit the accuracy of the final results to no better than ±10 per cent.

Additional errors were introduced because of pointing uncertainties coupled with the somewhat non-uniform response of each payload photomultiplier across the field of view. There were also errors associated with the ground recording of the telemetered flight data. These two sources contribute about ±5 to ± 10 per cent to the estimate of overall error. Finally, an estimate must be made of remaining systematic errors. A "best guess" is ±10 per cent. The RMS average of all the sources of error is ±15 per cent. Some of the factors are slightly wavelength dependent but their variation does not significantly affect the overall error estimates.

THE DATA

The spectra obtained on the rocket flights are presented in Table 2 and Figure 1. The data are divided into three spectral ranges (vertical lines in Figure 1) corresponding approximately to the range of most reliable data from each photometer. The dividing points are 2350 and 2800 Angstroms. The 2350 Angstrom wavelength is where energy from the second order spectrum begins to contaminate data from the short wavelength detector. The 2800 Angstrom point allows for 600 Angstroms of overlapping between the medium and long wavelength detector. The division into these sections has significance only for interpretation of the 13.041 spectra.

The spectrum of α Leo obtain in flight 4.251 is plotted directly, based on the thermopile absolute calibration at 2537 Angstroms and on the assumption that sodium salicylate has constant quantum efficiency. For this flight, calibrated data are available from only the short and medium wavelength detectors. The independent calibrations of the short and medium wavelength detectors agree within 5 per cent and the data are adjusted to the average value in the overlapping region surrounding 2350 Angstroms.

For flight 13.041, an absolute calibration exists only for the short wavelength detector. The relative spectral calibrations for the medium and long wavelength detectors are reliable, but their absolute level is suspect due to amplifier instabilities. The short wavelength calibration can be extrapolated to the longer wavelength flight data by normalizing the medium wavelength relative data to the short wavelength absolute values, and then normalizing the long wavelength relative data to the adjusted medium wavelength values. If this is done, the resultant RMS error range is about ±20 per cent in the long wavelength region. The resulting values in the 3300 to 3500 Angstrom region are about 15 per cent lower than the fluxes in that same range reported by Schild, Peterson, and Oke (1971). A much smaller error range, about ±10 per cent, could be attributed to the long wavelength values by normalizing directly to Schild, Peterson and Oke's ground-based observations. For the data presented in Table 2 and Figure 1, this normalization in the region 3300 to 3500 Angstroms has been carried out. No further adjustment of data has been made in the long wavelength region. In the medium spectral region, a linear adjustment has been applied to the data in order to match it simultaneously to the long wavelength data at 2800 Angstroms and to the short wavelength data at 2350 Angstroms.

The spectra of α Leo from the two different flights are not averaged. They indicate the repeatability of the whole payload calibration procedure. There is no significant difference between the two observations longward of 1400 Angstroms. Shortward of 1400 Angstroms the 13.041 observation is more reliable because a more detailed calibration was made in that region. and because post-flight recalibration showed no change from the pre-flight sensitivity. All four spectra presented as the results of the 13.041 flight have been treated identically and then averaged.

COMPARISON WITH OTHER OBSERVATIONS

Broad bandpass observations of the four target stars, as reported by five other groups of observers, are presented in Table 3.

The observations reported by Carruthers (1968) are almost a factor of two greater in value than the fluxes determined during these rocket observations. The ratios between the three stars are the same, within ± 10 per cent.

Chubb and Byram (1963) report a flux for α Leo that is about 50 per cent lower than the present observation. They observed none of the other stars discussed here.

The fluxes for α Leo and γ Ori reported by Smith (1967) have very large absolute error flags, which overlap the present data. The ratio of his fluxes for the two stars matches that from the 4.251 and 13.041 data within the present rocket error limits.

The values of flux levels determined by Yamashita (1968) are normalized to Smith's observations of αLeo, but they have a much larger scatter. Nevertheless, the spectral shape indicated by Yamashita agrees with the results of the scanner observations.

Campbell (1970) has made observations of α Leo using an absolutely calibrated set of broad band photometers. At 2150A, Campbell's observational error limits the error limits for the 4.251 observations overlap. The 13.041 data is separated from campbell's by the sum of our stated error limit s, i.e. the error 'flags' just touch.

An observation of α CMa with an instrument nearly identical to the ones used for this calibration series has been reported by Stecher (1970). His data is presented here in graphical form in Figure 2. Stecher's payload was calibrated in the same facilities as were 4.251 and 13.041; however, a different technicque of calibration and a different reference chain traceable to the NBS were used. Compared with the 13.041 observation, his reported flux levels are slightly lower (about 20 per cent) at 1650 and 1750 Angstroms and significantly lower (up to 30 per cent) at 2850 to 3150 Angstroms.

Earlier observations by Stecher (1969) and Stecher and Milligan (1962) longward of 1700 Angstroms infer similar spectral shapes, but the error limits on those data are larger than on Stecher's recent observation of α CMa.

The four stars observed during rocket flight 13.041 have also been observed using the Wisconsin Experiment Package aboard OAO-II, but at different times. The relative flux ratios derived from the OAO-II filter photometers at 1300, 1400, 1500, and 1600 Angstroms agree within error limits with the ratios derived from the rocket data. At 1900 and 2500 Angstroms, the fluxes measured by the OAO-II photometers have very wide error limits because of very high count rates. The longer wavelength OAO-II photometers were saturated and produced no data on these bright stars.

The relative shapes of the spectra determined by the OAO-II long wavelength scanner agree with the 4.251 and the 13.041 observations within about ± 5 per cent longward of 2200 Angstroms. Shortward of 2200 Angstroms, the OAO values increase, becoming 30 per cent higher than the rocket data at 1800 Angstroms, which is the short wavelength limit of the OAO-II scanner. This comparison is based on observational data supplied by B. Savage (personal communication) to Anne B. Underhill (1971).

Comparison with OAO-II scans of α Leo using the short wavelength scanner indicates agreement to within ± 15 per cent of the provisional calibration of the short wavelength scanner determined by A. Code (Personal communication). In the case of γ Ori and κ Ori, the rocket data is about 10 to 30 per cent lower than that determined by the provisional OAO-II calibration, the larger discrepancies occuring at shorter wavelength. The flux ratios between stellar spectra obtained using the short wavelength scanner data are not in as good agreement with the rocket data as are the ratios derived from the OAO-II photometer data.

In the spectral range longward of 3000 Angstroms, stellar spectra are measurable from the ground. From about 3000 to 3300 Angstrom large corrections must be made to the observations because of extinction of radiation by the earth's atmosphere, and large uncertainties exist in ground-based observations. Longward of 3300 Angstroms, accurate photometric observations, of stars can be made. For comparison to the present observations, the the absolute spectral energy distribution of α Lyrae determined by Oke and Schild (1970) is used. Spectra of three of the four stars observed by the rocket (α CMa, γ Ori, and α Leo) have been published by Schild, Peterson, and Oke (1971), photometrically referenced to the 1970 α Lyrae observation. Thirteen color photometric observations of all four stars have been reported by Mitchell and Johnson (1969). The ratio between the spectra of α CMa and α Leo can also be determined from the work of Aller, Faulkner, and Norton (1966). The errors in the relative flux ratios between stars using ground-based data are equal to or superior to the rocket ratios.

The data from these rocket observations and the other comparison observations are presented graphically in Figure 2. Only the best ultraviolet observations from Table 3 have been included in that figure. Also, only the ground-based observations of Schild, Peterson, and Oke (1971) are included in the figure.

DISCUSSION OF PRESENT DATA

After all calibration procedures have been completed and final flux values have been derived, there are still some suspected problem areas.

First, based entirely on the rocket data itself, is the "tie" with ground-based observations. From 3300 to 3500 Angstroms a dip can be observed in the spectra presented in Figure 1. This dip, or the corresponding hump at about 3500 Angstroms, is suspect, because it is in this region that sodium salicylate becomes transparent. Also in this spectral region the primary laboratory reference is switched from the sodium salicylate to tungsten-iodide irradiance standards calibrated by the NBS. There is a definite shift in sensitivity of the payload in this spectral region indicated by both calibration references. A judicious smoothing of the calibration curve could eliminate the 3400 Angstrom dip and also remove the 15 per cent discrepancy that develops when the short wavelength absolute calibration is extrapolated to meet the ground-based data. The present laboratory calibration data do not justify making this correction, but a systematic error may exist. This spectral region will be investigated intensively during the calibration of the next flight payload.

Second is the existence of some disagreement in the comparison data available in the short wavelength range. Preliminary data available from the University of Wisconsin calibration rocket (Bless, personal communication) indicates agreement with the present data from 2000 to 2800 Angstroms (2800 Angstroms is the long wavelength limit of the Wisconsin rocket data). Shortward of 2000 Angstroms the Wisconsin values for the spectrum of α Leo indicate a smooth tie with Carruthers (1968) values. The present rocket data is therefore about 30 to 50 per cent low, relative to the Wisconsin observations. This is a very disconcerting disagreement, because it is larger than the combined error flags of the two observations. A thorough reinvestigation of the 13.041 calibration procedures did not reveal any sources of systematic error that could account for the discrepancies. A weakness in the calibration below 2000 Angstroms is its reliance on the assumption that the quantum efficiency of sodium salicylate is wavelength independent. It is now possible to use calibrated photodiodes as standards in this spectral region, and the uncertainties due to sodium salicylate will be avoided on future flights.

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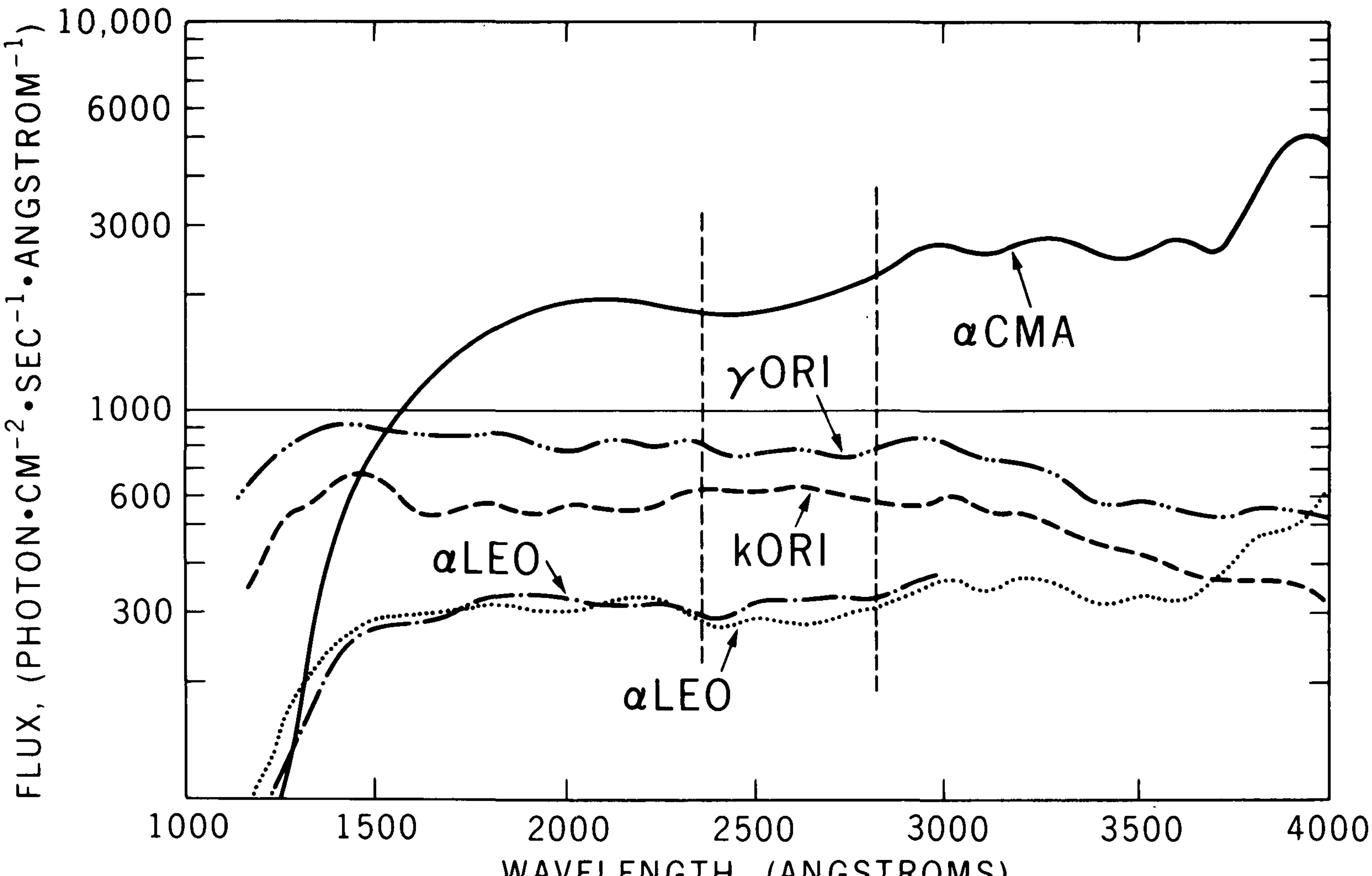

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Figure 1. Preliminary Stellar Spectra. The observation of αLeo from flight 4.251 ends at 3000 Angstroms. All other spectra are from flight 13.041. The short wavelength region is based on the present absolute calibration; the long, normalized to the observations of Schild, Peterson, and Oke(1971); and the medium, has been adjusted (see text).

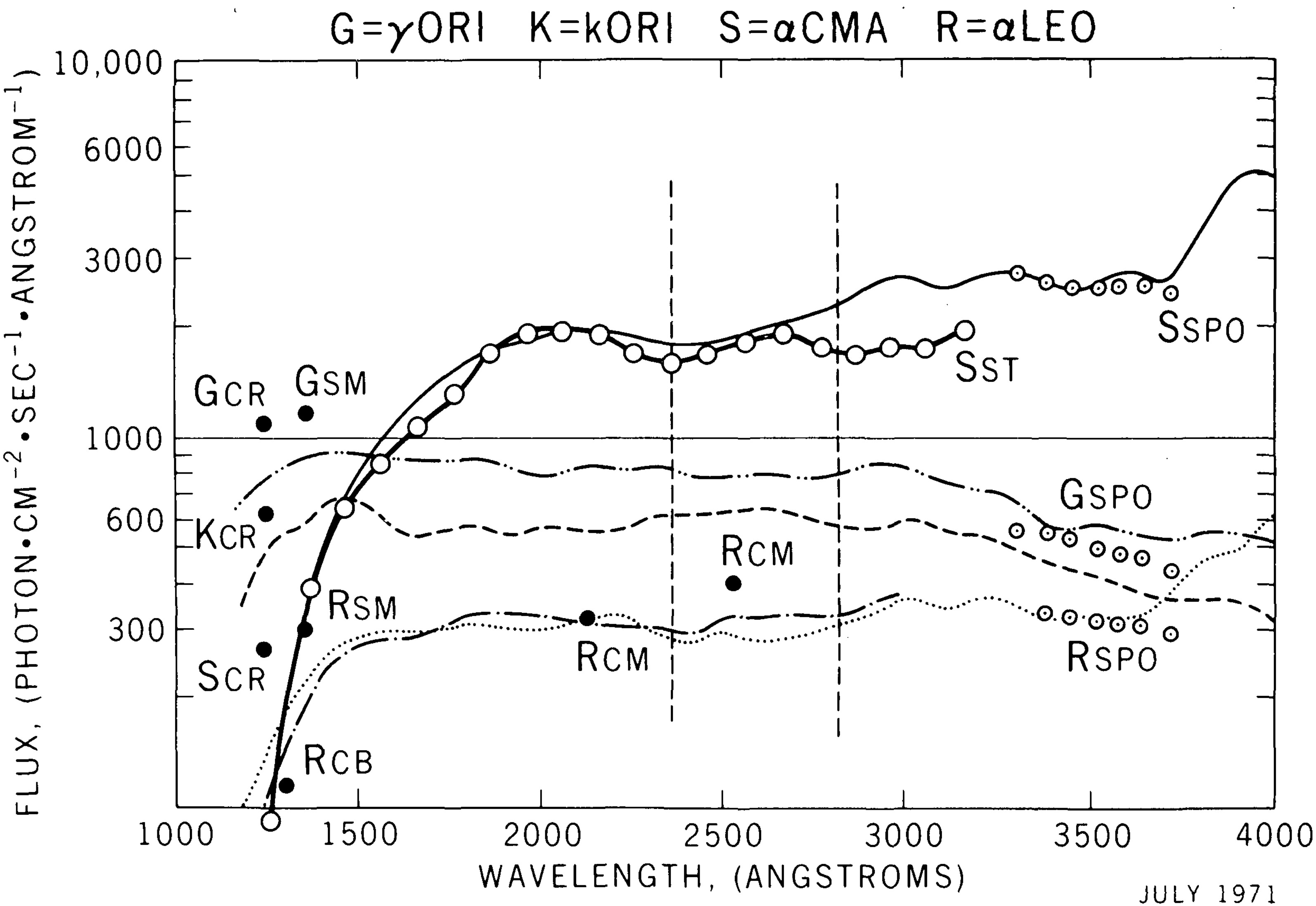

Figure 2. Other Observations. Comparison of the present observations with other reported flux values. [CR=Carruthers(1968): CB=Chubb & Byram(1963): SM=Smith(1967): SPO=Schild, Peterson, & Oke (1970): ST=Stecher(1970). See Figure 1 for identification of the present spectra.]

Table 1

Rocket Observations

Rocket Flight	Star	Sp.	V	Number of Scans
4. 251	αLeo	B7 V	1.36	2
13. 041	αCMa	A1 V	-1.47	1
	γOri	B2 III	1.64	6
	κOri	B0.5 Ia	2.04	2
	αLeo	B7 V	1.36	3

Table 2

Preliminary Stellar Spectra

(photon cm^{-2} sec^{-1} $Angstrom^{-1}$)

Wavelength (Angstroms)	αCMa (1)	γOri (1)	κOri (1)	αLeo (1)	αLeo (2)
1200	70	700	400	110	70
1300	197	850	580	190	160
1400	540	910	660	255	240
1500	780	900	660	290	280
1600	1100	880	540	300	290
1700	1400	860	540	305	300
1800	1630	870	590	320	335
1900	1720	820	550	305	335
2000	1800	760	580	305	325
2100	1950	820	560	325	320
2200	1850	800	560	330	320
2300	1730	820	610	300	305
2400	1670	760	620	230	290
2500	1700	770	620	300	315
2600	1820	780	640	285	330
2700	2000	770	600	300	330
2800	2180	800	600	305	320
2900	2530	850	590	345	340
3000	2670	820	620	370	---
3100	2500	750	550	355	---
3200	2720	720	540	380	---
3300	2700	650	480	360	---
3400	2450	570	450	310	---
3500	2430	580	420	330	---
3600	2700	550	390	320	---
3700	2450	510	380	365	---
3800	3850	540	380	470	---
3900	4900	540	375	490	---
4000	4700	520	335	620	---

(1) Data from Rocket 13.041
(2) Data from Rocket 4.251

Table 3

Other Ultraviolet Observations of the Target Stars

Star	Wavelength (Angstroms)	Wavelength Limits	Flux Value (photon cm^{-2} sec^{-1} A^{-1})	Absolute Error* (%)	Reference
αCMa	1270	1230-1350	275	±20	Carruthers (1968)
,,	1314	1290-1350	>205	NS	Chubb & Byram (1963)
γOri	1270	1230-1350	1118	±20	Carruthers (1968)
,,	1290	1230-1350	396	±30	Yamashita (1968)
,,	1314	1290-1350	>218	NS	Chubb & Byram (1963)
,,	1376	1280-1570	1143	±50	Smith (1967)
,,	1415	1350-1480	648	±15	Yamashita (1968)
κOri	1270	1230-1350	645	±20	Carruthers (1968)
,,	1290	1230-1350	201	±45	Yamashita (1968)
,,	1314	1290-1350	>264	NS	Chubb & Byram (1963)
,,	1415	1350-1480	292	±20	Carruthers (1968)
αLeo	1290	1230-1350	181	±45	Yamashita (1968)
,,	1314	1290-1350	123	NS	Chubb & Byram (1963)
,,	1376	1280-1570	304	±50	Smith (1967)
,,	1415	1350-1480	313	±20	Yamashita (1968)
,,	2150	1875-2525	342	±15	Campbell (1970)
,,	2550	2300-2900	407	±15	Campbell (1970)

*Reported by the author or not stated (NS).