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STELLAR SPECTROPHOTOMETRY FROM A POINTED ROCKET

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ABSTRACT

A 13-inch telescope with a three-channel photoelectric scanner was successfully flown on an Aerobee rocket. The whole rocket assembly was pointed at four program stars with an absolute accuracy exceeding 20 seconds of arc. Two photometric scans (of 20-sec duration) of each program star were made with a resolution of 10 Å. The observed stars were α CMa, A1 V; ϵ CMa, B2 II, ζ Pup, O5f; and γ^2 Vel, WC8. The spectrum of each star is presented in absolute energy units. A preliminary discussion of the spectra is made.

I. INSTRUMENTATION

Accurate stellar spectrophotometry requires both good stabilization and absolute pointing. The capability to achieve this has been developed at the Goddard Space Flight Center (Russell 1969). The system developed for the Aerobee rocket consists of a gyroscopic inertial-reference platform which operates a system of coarse gas jets and will point the rocket within a few degrees of each programmed celestial position. When the rocket is stabilized at the first target, a star tracker electronically scans an 8° field and selects the brightest star. It then gives a saturated error signal which controls the coarse jets until the star is within 25 minutes of arc. The star tracker then gives a proportional error signal, and the control of the rocket is done by a system of fine jets until null is reached. The fine jets then fire whenever the error exceeds the trip level, which is on the order of 5 seconds of arc. The error signal is in both pitch and yaw and is continuously telemetered to ground. When null is reached, the gyroscopes are caged to that position which corrects for any launch error and drift. When the time allotted for the observation is up, control is returned to the gyroscopes and they are torqued to the next target. The rocket follows the gyroscopes in an attempt to null the gimbal error.

The telescope had a 13-inch elliptical primary and a spherical secondary giving an f/10 beam. An entrance slot 10 × 15 minutes of arc was used. The spectrometer section consisted of a concave grating with 1200 lines mm^{-1}, a folding mirror with a magnification of 1.2, and three exit slits in the focal plane. The grating was rotated around an axis which was slightly tipped from a perpendicular to the entrance beam so that the folding mirror would not block the beam. The resulting spectrometer, which is rather straightforward but not experimentally intuitive, was designed by H. McKinley. All of the optics were coated with fast-fired aluminum overlaid with a thin layer of magnesium fluoride. The reflectance of the test plates coated at the same time exceeded 80 percent at Lα. The optics were mounted in an epoxy-filled aluminum-honeycomb cylinder which was fastened to the aerodynamical skin with a bulkhead at the bottom of the payload. This eliminated heating problems during launch. The optical payload was fabricated by the Kollmorgen Company. The Goddard system engineer was David Wright.

The detectors were an EMR 542F photomultiplier with a lithium fluoride window and a cesium telluride cathode, and two EMR 541N photomultipliers with sapphire windows and with bi-alkali cathodes. Each photomultiplier was used with a pulse amplifier which normalizes each pulse to one and then integrates the pulses to provide an analogue signal to the telemetry in three ranges a factor of 5 apart. The telemetry system was a pulse-position modulation transmitter which samples 5000 times a second and is divided into sixteen channels which were recorded digitally on magnetic tape. The telemetry system contained an accurate inflight calibration system.

The telemetry tape was processed in the Goddard computer complex. The stellar signals are received as a voltage as a function of time and were converted to flux versus wavelength. The experiment contained a wavelength-marker generator which was calibrated in the laboratory. This provided the wavelength to about 20 Å. Strong lines were then identified, and a final wavelength for each scan was assigned on this basis. Since the pointing was not exact, a correction to each point was made from the pointing-error signal. The wavelength correction was 25 Å per minute of arc.

II. CALIBRATION

The response of the telescope was determined in a vacuum calibration tank which consists of a 15-inch telescope with the exit slit of a vacuum monochromator placed at its focus. An LiF scattering plate was placed at the exit slit of the monochromator. This plate forms a new source which has the characteristics of a Lambert surface. The method of calibration was to set the monochromator on a wavelength which then fills the flight instrument with a monochromatic beam of light. The grating in the payload was then scanned until a response was obtained. The grating was then stopped, and the carriage in which the payload was mounted was moved in pitch and yaw until the maximum response was obtained. Then the response was recorded along with that of the monitors. One monitor consisted of a photomultiplier coated with sodium salicylate, and the other was a calibrated photomultiplier with a cesium telluride cathode. This was then repeated several times at 50 Å intervals, except near the endpoints where smaller intervals were used. The sodium salicylate was assumed to have a constant quantum efficiency in the ultraviolet. In this way the relative efficiency as a function of wavelength was obtained.

The relative calibration may be placed on an absolute basis by using a monitor which has been calibrated on an absolute basis and applying the appropriate geometric factor between it and the telescope. This procedure is still being checked. As an interim measure the absolute flux value was determined from α CMa at $\lambda 2537$ which had been previously calibrated by Stecher (1969) with an instrument that was simpler to calibrate. The resulting calibration should be taken as provisional. At $\lambda 1270$ the agreement with Carruthers (1968) was within a few percent. On the basis of photon statistics the relative scans between stars should be within 2 percent over the resolution-element of 10 Å. The electronic time constant was set to respond to 68 percent of the true value in the time necessary to scan the element with a resolution of 10 Å.

The rocket was fired from White Sands, New Mexico, 1966 November 21, at $10^{\rm h}00^{\rm m}$ U.T. The peak altitude was 102 miles. Although five stars were programmed, aerodynamic effects were too large for the fine controls on the fifth target. The control system, telemetry, and telescope were parachuted to the ground and recovered in working condition.

III. RESULTS

The stellar spectra are presented in the order that they were observed. In Figure 1 the middle-wavelength scan of α CMa, A1 V, $V = -1.46$, is presented. The unit is 10^{-9} erg cm^{-2} s^{-1} Å^{-1}. The spectrum observed contains a large number of unresolved lines. The positions of the strongest multiplets of Fe I, Fe II, Si I, Si II, Mg I, Mg II are marked above the spectrum, and most of them are clearly present. Lines of other metals, such as V I, V II, Cr I, Cr II, Ti I, and Ti II, are also present. It has been shown by Strom, Gingerich, and Strom (1966) and others that Sirius is overabundant in metals. The blanketing by closely spaced lines is quite severe. An attempt to determine the amount of blanketing is being made.

Figure 2 shows the spectrum of Sirius recorded by the short-wavelength detector. The most prominent feature is due to hydrogen Lα at λ1216. The line is sufficiently broad that the profile can be considered useful.

The strong depression of the continuum below λ1800 is due to neutral silicon. There is a one-to-one correspondence between the features in the shock-tube spectra of neutral silicon (Rich 1967) and this spectrum. With this spectrum and recent infrared measurements the complete spectrum ot Sirius has now been observed. Since the distance,

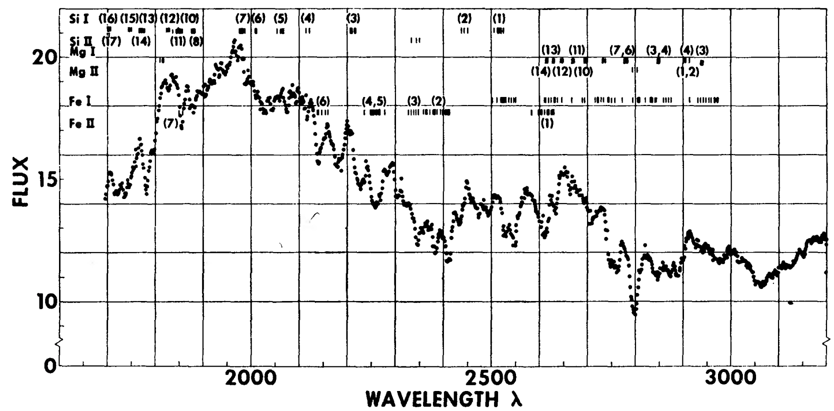

FIG. 1.—αCMa, A1 V, observed with the middle-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

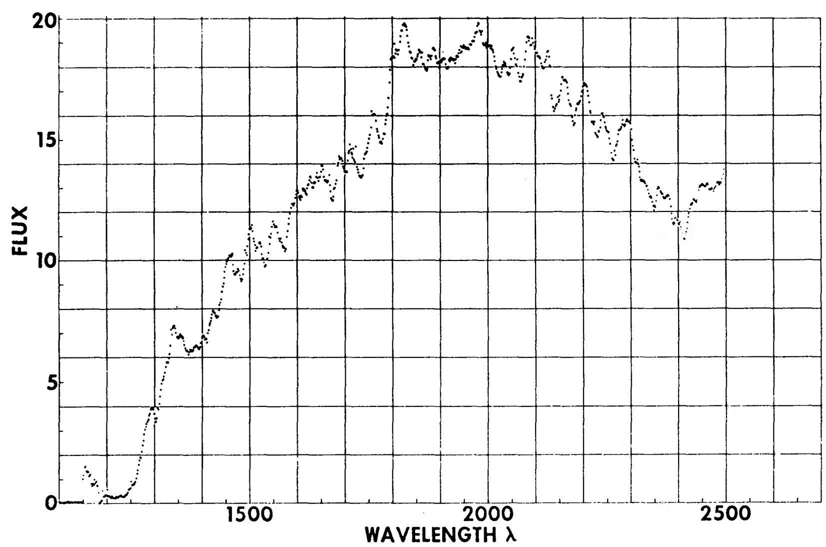

FIG. 2.—α CMa, A1 V, observed with the short-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

angular diameter, and mass are known, a detailed model fitting is in progress (Fischel, Klinglesmith, and Stecher 1969).

Figure 3 shows the spectrum obtained by the middle-wavelength detector on the B2 II star ϵ CMa, $V = 1.50$. The continuum is consistent with a model containing no lines at 20160° K, $\log g = 3.8$ (Mihalas 1965). The blanketing near 2000 Å, however, is considerably greater than that predicted by Elst (1967). The features have not been positively identified. Higher resolution and more complete atomic data are prerequisites for this.

Figure 4 shows the short-wavelength spectrum of ϵ CMa. The major spectral lines are due to H I, C II, C III, C IV, Si III, Si IV, He II, Al II, Al III, and Fe III. The continuum progressively falls below a continuous model at shorter wavelengths, reaching a difference of 0.8 mag at λ1300. The color excess for this star is less than 0.02 mag, so from Stecher (1965) less than about 0.14 mag can be attributed to interstellar extinction. An error in the shape of the relative calibration curve could depress the flux in this

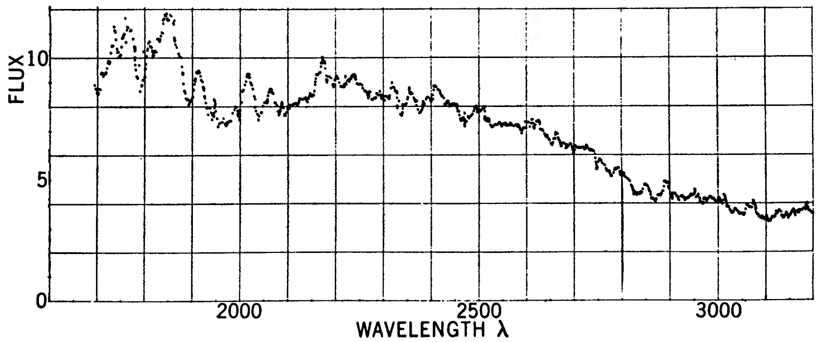

FIG. 3.—ϵ CMa, B2 II, observed with the middle-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} $Å^{-1}$.

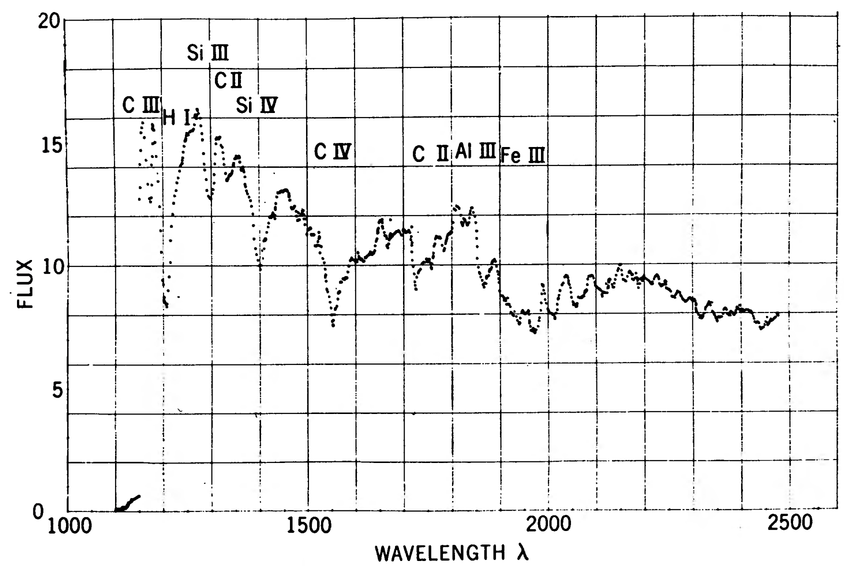

FIG. 4.—ϵ CMa, B2 II, observed with the short-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} $Å^{-1}$.

manner. If this were the case, the depression of the short-wavelength flux in Sirius would also have to be attributed to this. The depression in Sirius, however, is completely explainable in terms of an overabundance of neutral silicon by a factor of 5 or less. There is good evidence in the visible spectrum for such an overabundance (Strom *et al.* 1966). The inclusion of strong lines in the model (Mihalas and Morton 1965) results in a considerable improvement. The strong lines in ϵ CMa are clearly wider than the lines of the model, an observation which questions the value of the damping constant used in their computation. If the thousands of lines due to metals ionized two and three times were taken into account in the model, perhaps the discrepancy would vanish. Qualitatively, it would appear that with each stage of ionization the blanketing in a star moves 1000 Å to shorter wavelength.

The spectrum of ζ Pup, O5f, $V = 2.25$, $B - V = -0.27$ obtained with the middle detector is shown in Figure 5, and again the energy is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1} at the Earth. Between 1800 and 3100 Å (the endpoints of each scan are photometrically less certain) the continuum can nicely be represented by a 28000° K, log $g = 4$, continuous model (Mihalas 1965). The correction for interstellar extinction, though small in the visible, will significantly increase the derived effective temperature. If the intrinsic $B - V$ color for an O5 star is $(B - V)_0 = -0.33$, then the color excess is 0.06 mag, and at λ2000 the flux must be raised by 0.30 mag. This would be the effective temperature up to almost 40000° K and would be entirely consistent with the effective temperature assigned to the O5 classification by Hickok and Morton (1968). The difference between a 40000° and a 50000° K model at 2000 Å is only 0.1 mag when the models are normalized in the visible. An error of 0.02 mag in the color excess would result in 0.1 mag at λ2000 and therefore a large change in effective temperature.

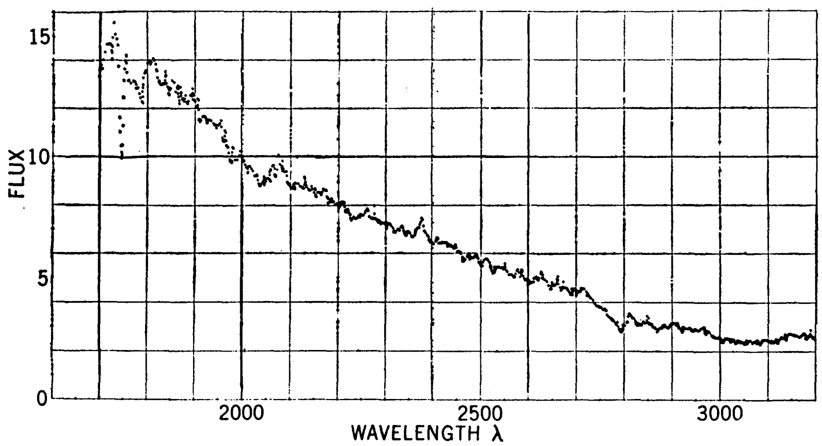

FIG. 5.—ζ Pup, O5f, observed with the middle-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

In Figure 6, the short-wavelength spectrum of ζ Pup is presented. It is immediately apparent that the star is not in hydrostatic equilibrium. The resonance lines of C IV, Si IV, and N V all show a strong P Cygni profile. This phenomenon appears to be present in all resonance lines. Furthermore, the excitation in this star is sufficiently high that nonresonance lines also show this phenomenon, in particular the N IV line at λ1718 which is 16.13 V above the ground state. The absorption minimum is separated from the emission peak by approximately 15 Å in the case of C IV. Measurement of this shift is best done from photographic spectrograms (Carruthers 1968; Morton, Jenkins, and Brooks 1969; Smith 1970) since the data presented here have a resolution of 10 Å and do not contain an absolute wavelength calibration. Qualitative interpretation of the shift in terms of radial outflow of material is straightforward, but a quantitative interpretation to determine the velocity and mass flow is quite model-dependent. The electronic time constant and the 10 Å slit width attenuated the emission peak and prevented the signal from going to zero at the core of the absorption lines. Indications are that it will go to zero when the instrument profile correction is applied.

The absorption at λ1216 may be assumed to be due to interstellar neutral hydrogen. In this case the line is formed by radiation damping and gives an upper limit to the amount of neutral hydrogen between us and the star. The small equivalent width of ~4 Å is consistent with low interstellar extinction.

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In Figure 7 the middle-wavelength spectrum of γ^2 Vel, WC 8 + O7, $V = 1.83$, is presented. If we assume that the extinction correction is the same as that for ζ Pup, an effective temperature of $\sim$4000° K is obtained from the estimated position of the continuum. There are numerous emission lines present in this spectrum; however, only three have been clearly identified: the C IV line at λ2524, log $gf = 0.999$; the C III $^1p^o$–^1D

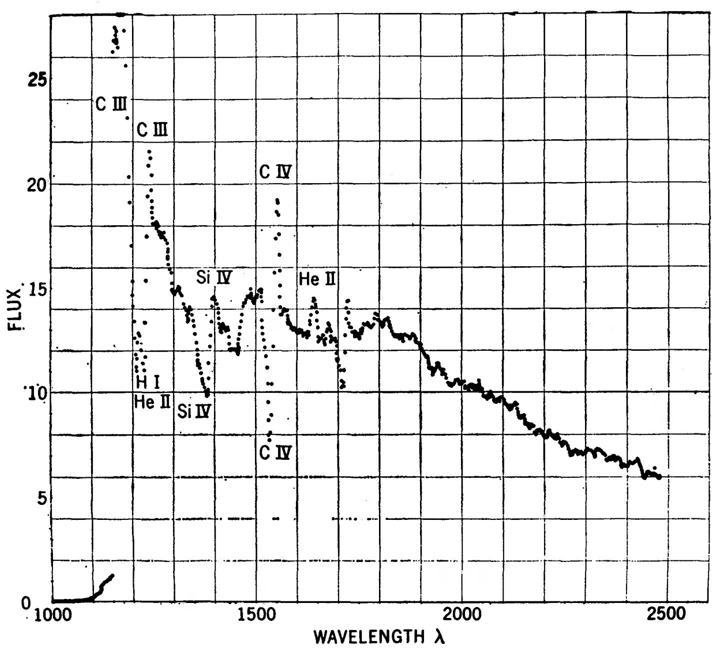

FIG. 6.—ζ Pup, O5f, observed with the short-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

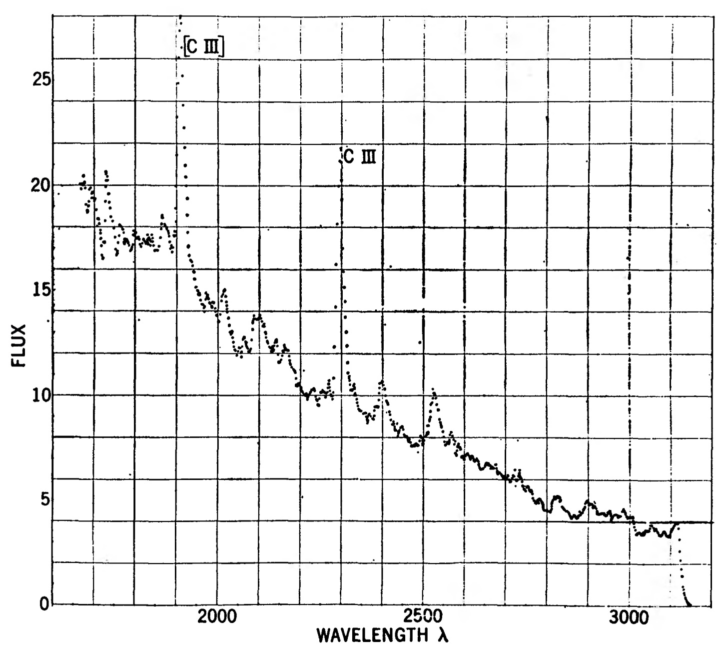

FIG. 7.—γ^2 Vel, WC 8, observed with the middle-wavelength detector. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

line at λ2297, log $gf = 0.15$; and the intercombination line of C III at λ1909, $gf = 3.1 \times 10^{-7}$. The question of how the λ1909 line originates has been investigated on a preliminary basis (Stecher and West 1968) and may be due to laser action.

Figure 8 is the short-wavelength spectrum of γ^2 Vel. The broad general absorption between λ1700 and λ1300 is due to molecular oxygen in the Earth's atmosphere. This can be corrected for in a fairly precise manner, since the return scan occurred at a lower altitude. A by-product of this correction will be a factor of 10 improvement in our knowledge of the nighttime O_2 concentration between 120 and 140 km.

The resonance lines are again in emission with absorption cores shifted to shorter wavelengths, although the velocity indicated is about half that of ζ Pup. The λλ1909 and 2296 lines of C III are present. The Hα line of He II appears quite broad. Many lines either are unidentified or have ambiguous identifications. This is due in part to the low

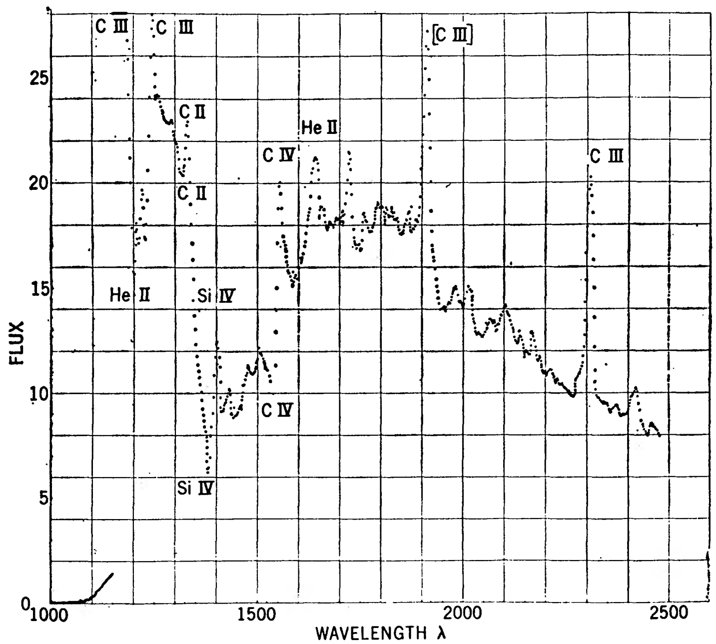

FIG. 8.—γ^2 Vel, WC 8, observed with the short-wavelength detector. Telluric absorption by O_2 is present. Flux is in units of 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

resolution; however, the atomic data are lacking for many of the high-excitation states present in this star. The similarity of the hydrogen Lα equivalent width in γ^2 Vel to that in ζ Pup indicates a low column density for neutral hydrogen and implies the correctness of the correction for interstellar extinction. A number of weak lines that could be due to interstellar ions are apparently present in both ζ Pup and γ^2 Vel. A search for quarks and quarked ions has been negative.

Publication of a complete set of flux values as a function of wavelength and equivalent width for emission and absorption lines is planned for this flight and subsequent rocket flights. The author recommends that α CMa, ε CMa, and ζ Pup be used as provisional standards.

The Aerobee stabilization system was started and followed at all stages by J. E. Kupperian, Jr., and A. Boggess III. The stabilization project manager was W. Russell; the optical systems engineer was D. Wright. The digital telemetry was developed by R. Stattel. Invaluable assistance was obtained from G. Baker, J. Shannon, E. Serra, A. Stober, R. Scolnik, and C. Clifton. To these people in particular, and to many more who participated in the success of this project, I am deeply grateful.

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