THE ASTROPHYSICAL JOURNAL, 211:432–442, 1977 January 15

THE SPECTRAL ENERGY DISTRIBUTION OF ZETA PUPPIS AND HD 50896

ALBERT V. HOLM AND JOSEPH P. CASSINELLI
Washburn Observatory, University of Wisconsin, Madison
Received 1976 May 17

ABSTRACT

The ultraviolet spectral energy distribution of the O5f star ζ Pup and the WN5 star HD 50896 are derived from OAO-2 observations with the new calibration of Bless, Code, and Fairchild. An estimate of the interstellar reddening of the Wolf-Rayet star of $E_{B-V} = 0.12$ is determined from the size of the characteristic interstellar extinction bump at 4.6 μm^{-1}. After correction for extinction, both stars show a flat energy distribution in the ultraviolet. The distribution of HD 50896 from 1100 Å to 2 μm is in good agreement with results of extended model atmospheres, but some uncertainty remains because of the interstellar extinction correction. The absolute energy distribution of ζ Pup is fitted by a 42,000 K plane-parallel model if the model's flux is adjusted for the effects of electron scattering in the stellar wind and for UV line blanketing that we determined empirically from high-resolution *Copernicus* satellite observations. To achieve this fit, it is necessary to push both the spectroscopically determined temperature and the ultraviolet calibration to the limits of their probable errors.

Subject headings: spectrophotometry — stars: individual — stars: Of-type — stars: Wolf-Rayet — ultraviolet: spectra

I. INTRODUCTION

The object of this paper is to investigate the continuous energy distribution of two well-studied very early-type stars which have been reported to have peculiar energy distributions. In each case the anomalous continuum has been attributed to the effects of extended stellar atmospheres (Van Blerkom and Patton 1972; Heap 1972; Castor 1974). Comparisons of the observed continua with the results of model atmosphere calculations will be made to test this idea.

The ultraviolet flux distributions of ζ Pup and HD 50896 are derived here from OAO-2 observations. Preliminary data on these objects have been presented before (Heap 1972; Smith 1972), but we now include the results of more recent calibrations. The data are corrected for interstellar extinction and combined with conventional photometry to provide continuous energy distributions over a wide range in wavelength.

The line spectrum of ζ Pup can best be explained by assuming the effective temperature is 50,000 K (Baschek and Sholz 1971; Heap 1972; Conti 1973). The angular diameter has been measured by Davis *et al.* (1970), and therefore intrinsic surface fluxes can be derived. These surface fluxes imply a temperature of only 32,500 ± 1930 K (Davis *et al.* 1970; Code *et al.* 1976). This discrepancy has been discussed by Heap (1972), Conti (1973), Castor (1974), and Mihalas and Hummer (1974) and explained as an effect of an extended stellar atmosphere. The true explanation is still obscure, since Castor, Abbott, and Klein (1975, hereafter CAK) have found that their dynamical models are not extended at the depths where the optical continuum is formed. Thus we feel that further analysis of the continuum flux distribution is necessary.

HD 50896 is one of the apparently brightest Wolf-Rayet stars and is one of the few Wolf-Rayet stars which has not been confirmed to be a binary. A suspicion that HD 50896 is an undetected binary has been created by its variability in emission-line profiles, in optical continuum brightness, and in polarization (Wilson 1948; Serkowski 1970; Moffat and Haupt 1974; Schmidt 1974). Nevertheless, the case for HD 50896 being a binary is weak because the observations are contradictory. Wilson (1948) and Barbon *et al.* (1965) have found no correlation between the displacements of the different lines. Moreover, the various authors find different and incompatible periods for different phenomena. The absence of a common period greatly weakens the arguments for the binary nature. These variable phenomena may also be taken as evidence of large-scale quasi-periodic disturbances in the atmosphere of HD 50896. The current state of observational data and of interpretation appears to admit either possibility. Finally, no spectroscopist has noted the presence of a secondary spectrum (Wilson 1948; Pyper 1966; Hiltner and Schild 1966; Smith 1968; Walborn 1974). The absence of a secondary spectrum implies that, if a secondary exists, it must be considerably fainter than the Wolf-Rayet component, so the flux distribution probably is an excellent representation of that of a single WN5 star.

Optical photometry of HD 50896 obtained by Kuhi (1967) shows that its color temperature, like that of other Wolf-Rayet stars, decreases toward the red part of the spectrum. This behavior, which suggests a flat energy distribution, extends into the infrared to at least 2 μm (Gehrz and Hackwell 1974) and can be explained by an extended model atmosphere. Van Blerkom and Patton (1972) achieved a reasonable fit to the visible continuous energy distribution with a gray local thermodynamic equilibrium (LTE) extended atmosphere model that has an effective temperature of 50,000 K and an absorption coefficient that varies with radius as $1/r^{2.1}$.

Much research has been done recently on extended and expanding model atmospheres for hot stars. Hydrostatic model atmospheres for very hot stars have been calculated by Cassinelli (1971*a*, *b*) and Castor (1974) in the LTE approximation, and by Mihalas and Hummer (1974) and Kunasz, Hummer, and Mihalas (1975) with non–LTE effects. Most of the models are extended in the sense that the density scale height at optical depth unity is not negligibly small compared with the radius of curvature at that point. Cassinelli (1971*b*) noted that such models have the anomalously flat energy distribution characteristic of Wolf-Rayet stars in the visual (Kuhi 1967). Castor (1974) showed that his extended model could explain the anomalously low effective temperature of ζ Pup (Davis *et al.* 1970). By showing that non–LTE effects eliminated the emission Balmer jump of the earlier extended models, Mihalas and Hummer (1974) and Kunasz, Hummer, and Mihalas (1975) showed that the observed absence of emission jumps was not evidence for nonextension of the atmosphere.

The relevance of these static, extended models to early-type stars has been questioned on both theoretical and observational grounds. There is clear evidence from P Cyg profiles of strong spectral lines that the outer layers of the atmospheres are not hydrostatic but are expanding supersonically. Expanding models by Lucy and Solomon (1970) and by CAK in which the effects of spectral lines on the structure of the atmosphere are treated explicitly have very shallow continuum-formation regions. In these models, the effects of sphericity on the energy distribution in the optical continuum are slight, but the ultraviolet continuum is affected by line blanketing. Cassinelli and Hartmann (1975) made special efforts to calculate flow models with extended continuum-formation regions. Unfortunately, to accomplish this they were forced to adopt luminosities larger by a factor of 2 than those determined from stellar interior calculations (Castor 1974). Thus those models calculated with realistic physical assumptions have not produced "flat" energy distributions, and those models with "flat" distributions have required unrealistic assumptions.

In the next section we discuss the observations and the data-reduction techniques. In § III we discuss the corrections to be made for interstellar extinction. After correction for extinction, we find that the energy distributions of both stars are flatter than expected for stars with their presumed $T_{\rm eff}$. In ζ Pup, the distribution can almost be reproduced by a model like that of CAK. HD 50896, the Wolf-Rayet star, is fitted by the model of Cassinelli and Hartmann (1975), a model having an extended optical continuum-formation region. In § IV we summarize the work and suggest some directions for future investigations.

II. OBSERVATIONS AND DATA REDUCTION

Each star was observed with the stellar photometers and with both objective-grating scanning spectrometers. The filter photometry of ζ Pup was obtained during 1971 May 4–5. The scans of ζ Pup were obtained during 1970 September 13–16 while the observatory pointing was controlled by the bore-sighted star-tracker (BST). The BST inhibits observatory motion, so shifts of the spectrum during a scan are reduced to ± 0.3 Å. The middle-ultraviolet, from 2.7 μm^{-1} to 5.4 μm^{-1}, was scanned nine times with 20 Å resolution by scanning spectrometer 1 (SP1). The far-ultraviolet, from 5.56 μm^{-1} to 9.09 μm^{-1}, was scanned 11 times with 10 Å resolution by scanning spectrometer 2 (SP2).

HD 50896 was observed with the stellar photometers on eight occasions between 1968 December 28 and 1972 October 20. It was scanned twice by SP1 on 1969 September 30. Nine SP2 scans from 1970 September 17, 1971 September 27, and 1972 October 20 were used in this work. All the observations of HD 50896 were obtained when the observatory pointing was controlled by the gimballed star-trackers (GST). Although the jitter is small when the observatory pointing is controlled by a given combination of gimballed star-trackers, pointing shifts of as much as 1′ may occur following a change in GST combination. A 1′ motion could cause a discontinuous shift in the spectrum by as much as 10 Å, depending on the relative orientation of the motion and the scanner axis. (To amend a statement in Code *et al.* 1970, we note here that a motion of 30″ along the spectrometer dispersion corresponds to a displacement of 5 Å in SP2.) Although changes in GST combinations took place during most of the scans used here, there are no indications of large errors in the data.

Doherty (1972) and Leckrone (1973) have discussed many of the problems encountered in reducing OAO-2 filter photometry. We have used many of the techniques used by these authors. The corrections for optical degradation were derived from repeated observations of stars with spectral types from O7 to B3. The absolute calibration constants, K_λ, given in Table 1, are from Code (1975). These constants replace the earlier constants, C_λ (Doherty 1972) and $-2.5 \log \Delta_\lambda$ (Leckrone 1973). In the system defined by these constants, $m(\lambda) = 0$ implies that f_λ is 3.62×10^{-9} ergs cm^{-2} s^{-1} Å^{-1}.

The magnitudes derived from filter photometry are given in Table 1. No magnitudes are given for ζ Pup for stellar photometer 1 (S1) or stellar photometer 2 (S2), because the analog measurements were saturated at even the lowest gains. Magnitudes for HD 50896 were derived from the S2 measurements because the strong ultraviolet flux of this star minimizes the errors due to red leaks in the S2 filters. The stellar photometer 3 (S3), filter 5 (5.96 μm^{-1}) measurements of both stars are presented here but were not used in

TABLE 1

UV FILTER PHOTOMETRY

Instrument	$1/\lambda$ (μm^{-1})	λ (Å)	$\Delta\lambda$ (Å)	K_λ*	M_λ ζ Pup	M_λ HD 50896
S1F3.......	2.35	4250	860	7.88	...	5.92
S1F1.......	3.01	3320	520	6.27	...	5.23
S1F4.......	3.35	2980	410	6.05	...	5.16
S2F2.......	3.37	2960	430	6.33	...	5.16
S3F2.......	4.06	2460	360	4.35	−0.66	4.71
S2F5.......	4.19	2380	330	5.38	...	4.65
S2F1.......	4.91	2040	490	4.66	...	4.21
S3F1.......	5.22	1910	260	2.27	−1.39	3.95
S3F5.......	5.96	1680	270	0.01	−1.71	3.35
S4F1.......	6.43	1550	270	1.24	−1.93	2.76
S4F3.......	6.99	1430	240	0.97	−2.22	2.64
S4F4.......	7.51	1330	185	−0.19	−2.42	2.39
No. Obs...	...	...	...	...	4	8

* Additive calibration constant.

analysis because, since half of that filter had half the transparency of the other half, large errors were caused.

The magnitudes given for HD 50896 represent averages. No attempt had been made to observe that star explicitly for variability. The maximum deviations at 3.01 μm^{-1}, 4.06 μm^{-1}, and 6.43 μm^{-1} are 0.04, 0.15, and 0.15 mag, respectively. These numbers represent upper limits to the observed variability, because they include the effects of errors in degradation function and of bright field stars.

The SP2 scans of both stars were corrected for skylight and dark counts and for optical degradation (Holm and Meade 1976), and converted into absolute fluxes using the new calibration of Bless, Code, and Fairchild (1976). The principal sources of skylight for SP2 are starlight scattered in the instrument and solar hydrogen Lα scattered by the geocorona into the field of view. Geocoronal Lα is observed, regardless of the wavelength range being measured in the stellar spectrum, because of the objective-grating nature of the instrument. The scanner counts caused by geocoronal Lα vary during a scan because the Lα intensity varies with the location of the observatory and because of geometrical attenuation by the slat collimators. For ζ Pup, the variations in skylight are insignificant compared with the stellar signal. Therefore the ζ Pup scans were corrected using the method described by Bless and Savage (1972). For HD 50896, the skylight is comparable to the stellar signal and the variations in skylight represent about 20–25% of the stellar continuum signal at the long-wavelength end of the scans. To estimate the contamination, we obtained a SP2 scan of the sky near HD 50896 on 1972 October 20. The sky measurement was smoothed and corrected by small amounts to allow for differences in observatory position between the scans of the star and of the sky, in attenuation by the collimators, and in dark count rates. After the subtraction of the estimated skylight, the individual scans were aligned in wavelength and summed.

The SP1 scans were corrected for skylight (Gallagher 1972), for optical degradation (Navach and Meade 1976), and for the relative calibration of the instrument determined from the work of Bless, Code, and Fairchild (1976). As stated by Code *et al.* (1976), the absolute level of SP1 scans cannot be determined from the data themselves, because of electronic problems in the instrument package. Since the relative sensitivity remains constant for this instrument (after correction for optical degradation), the absolute level can be determined by reference to known fluxes for the star. For ζ Pup, these known fluxes are from the scanner observations of Davis and Webb (1974) in the optical region and the SP2 scans at short wavelengths. We normalized the Davis and Webb data to the Hayes and Latham (1975) relative energy distribution of Vega and to the Johnson *et al.* (1966) *V*-magnitude. The absolute calibration of the *V*-magnitude is from Code (1973). The level of the SP1 scans was adjusted until the best fit was attained at both ends of the spectrum, as judged by eye. A different procedure, using OAO filter photometry, was used to normalize the SP1 scans of HD 50896. This change was made because the presence of strong emission lines made fitting the middle-ultraviolet to the visual and far-ultraviolet difficult, because the probable errors in the SP2 fluxes are relatively large and because filter photometry is available at seven wavelengths in the SP1 wavelength range. In this procedure we integrated the relative flux distribution derived from SP1 through the OAO-2 filter transmission curves. Then we adjusted the SP1 fluxes until a best fit was obtained with the fluxes derived from the filter photometry.

We list the fluxes derived for both stars in Table 2.

Figure 1 shows the scanner fluxes as well as fluxes derived from OAO filter photometry and from optical and infrared photometry. The optical data for ζ Pup have been described above. The infrared fluxes of ζ Pup are from the Johnson *et al.* (1966) *IJK* photometry. This broad-band photometry was calibrated by fitting the Johnson (1964) observed solar colors to colors calculated using a mean of the Labs and Neckel (1968) and Arvensen, Griffin, and Pearson (1969) solar flux distribution. The optical scan of HD 50896 from Kuhi (1966) is normalized to the relative energy distribution of Vega (Hayes and Latham 1975) and the narrow-band photometry of Smith (1968). The infrared photometry of HD 50896 is from Gehrz and Hackwell (1974) using the calibration of Gehrz, Hackwell, and Jones (1974).

The UV fluxes for HD 50896 derived from filter photometry tend to lie above those from the scans because of the effect of strong emission lines. For both HD 50896 and ζ Pup, the filter measurement at 7.5 μm^{-1} lies above the scanner measurements. This may be caused by inaccuracies in the calibration of that filter, by variations in the stellar radiation, or, especially in HD 50896, by errors in the photometry. For ζ Pup, the filter measurement at 4.1 μm^{-1} also is high. The star is so bright in that wavelength region that the filter measurement is near the upper limit for useful data. Therefore, we regard that filter measurement as

TABLE 2

UV Fluxes from the Scanning Spectrometers

λ (Å)	1/λ (μm^{-1})	log f_ν ζ Pup	log f_ν HD 50896	λ (Å)	1/λ (μm^{-1})	log f_ν ζ Pup	log f_ν HD 50896	λ (Å)	1/λ (μm^{-1})	log f_ν ζ Pup	log f_ν HD 50896
1150....	8.696	−19.70	...	1700....	5.882	−19.78	−22.01	2697....	3.708	−19.94	−22.08
1160....	8.621	−19.76	...	1710....	5.848	−19.81	−21.66	2718....	3.680	−19.94	−21.97
1170....	8.547	−19.76	...	1720....	5.814	−19.71	−21.49	2738....	3.652	−19.95	−21.75
1180....	8.475	−19.75	...	1730....	5.780	−19.70	−21.78	2759....	3.625	−19.96	−22.00
1190....	8.403	−19.78	−21.90	1740....	5.747	−19.72	−21.88	2779....	3.598	−19.96	−22.10
1200....	8.333	−19.93	−21.91	1750....	5.714	−19.72	−21.93	2800....	3.571	−19.98	−22.12
1210....	8.264	−19.93	−22.05	1760....	5.682	−19.72	−21.97	2821....	3.545	−19.97	−22.10
1220....	9.197	−20.03	−22.21	1770....	5.650	−19.72	−21.96	2841....	3.520	−19.97	−22.10
1230....	8.130	−20.06	−21.85	1780....	5.618	−19.72	−21.85	2862....	3.494	−19.98	−22.09
1240....	8.064	−19.75	−21.60	1790....	5.587	−19.72	−21.92	2882....	3.469	−19.98	−22.10
1250....	8.000	−19.70	−21.50	1800....	5.556	−19.72	−21.88	2903....	3.445	−19.98	−22.09
1260....	7.936	−19.73	−21.68	1810....	5.525	−19.73	−21.86	2924....	3.420	−19.99	−22.11
1270....	7.874	−19.73	−21.77					2944....	3.396	−20.00	−22.09
1280....	7.812	−19.71	−21.72	1815....	5.508	−19.76	−21.88	2965....	3.373	−20.00	−22.05
1290....	7.752	−19.71	−21.69	1836....	5.446	−19.75	−21.92	2985....	3.350	−20.01	−22.02
1300....	7.692	−19.74	−21.74	1857....	5.384	−19.76	−21.92	3006....	3.327	−20.01	−22.05
1310....	7.634	−19.74	−21.72	1878....	5.324	−19.76	−21.96	3026....	3.304	−20.01	−22.08
1320....	7.576	−19.75	−21.77	1899....	5.265	−19.77	−11.98	3047....	3.282	−20.01	−22.08
1330....	7.519	−19.76	−21.72	1920....	5.208	−19.78	−21.95	3067....	3.261	−20.02	−22.08
1340....	7.463	−19.75	−21.80	1941....	5.151	−19.80	−22.02	3087....	3.239	−20.02	−22.07
1350....	7.407	−19.77	−21.92	1962....	5.096	−19.81	−21.97	3108....	3.218	−20.01	−22.07
1360....	7.353	−19.81	−21.78	1983....	5.042	−19.82	−21.92	3128....	3.197	−20.01	−22.07
1370....	7.299	−19.86	−21.70	2004....	4.989	−19.83	−22.03	3148....	3.176	−20.01	−22.03
1380....	7.246	−19.91	−21.71	2025....	4.938	−19.84	−22.06	3168....	3.156	−20.01	−22.03
1390....	7.194	−19.80	−21.84	2046....	4.887	−19.85	−22.07	3189....	3.136	−20.02	−21.73
1400....	7.143	−19.70	−21.80	2067....	4.837	−19.86	−22.06	3209....	3.116	−20.02	−21.58
1410....	7.092	−19.73	−21.73	2088....	4.789	−19.87	−22.09	3230....	3.096	−20.02	−21.91
1420....	7.042	−19.73	−21.72	2109....	4.741	−19.87	−22.07	3250....	3.077	−20.02	−22.02
1430....	6.993	−19.74	−21.82	2130....	4.694	−19.87	−22.03	3271....	3.058	−20.02	−22.04
1440....	6.944	−19.78	−21.86	2151....	4.648	−19.88	−22.00	3291....	3.039	−20.02	−22.02
1450....	6.897	−19.79	−21.78	2172....	4.604	−19.88	−22.10	3311....	3.020	−20.02	−22.02
1460....	6.849	−19.75	−21.73	2193....	4.560	−19.89	−22.12	3332....	3.002	−20.03	−22.02
1470....	6.803	−19.70	−21.67	2214....	4.516	−19.89	−22.11	3352....	2.983	−20.04	−22.00
1480....	6.757	−19.67	−21.51	2235....	4.474	−19.89	−22.12	3372....	2.965	−20.04	−21.99
1490....	6.711	−19.66	−21.46	2256....	4.432	−19.90	−22.04	3393....	2.948	−20.05	−22.00
1500....	6.667	−19.64	−21.55	2277....	4.392	−19.90	−22.13	3413....	2.930	−20.05	−21.98
1510....	6.622	−19.62	−21.72	2298....	4.351	−19.90	−22.11	3433....	2.912	−20.05	−21.99
1520....	6.579	−19.67	−21.91	2319....	4.312	−19.89	−22.02	3454....	2.895	−20.05	−21.95
1530....	6.536	−19.95	−22.01	2340....	4.273	−19.89	−22.14	3474....	2.878	−20.05	−21.69
1540....	6.494	−19.78	−21.99	2361....	4.235	−19.90	−22.13	3494....	2.862	−20.06	−21.67
1550....	6.452	−19.51	−21.50	2382....	4.198	−19.90	−22.01	3515....	2.845	−20.05	−21.90
1560....	6.410	−19.59	−21.56	2403....	4.161	−19.90	−21.99	3535....	2.829	−20.04	−21.98
1570....	6.369	−19.64	−21.76	2424....	4.125	−19.89	−22.07	3555....	2.812	−20.05	−21.99
1580....	6.329	−19.66	−21.81	2445....	4.090	−19.90	−22.12	3576....	2.796	−20.06	−21.99
1590....	6.289	−19.68	−21.83	2466....	4.055	−19.90	−22.15	3596....	2.781	−20.06	−21.98
1600....	6.250	−19.71	−21.85	2487....	4.021	−19.91	−22.12	3617....	2.765	−20.06	−21.99
1610....	6.211	−19.74	−21.83	2508....	3.987	−19.91	−21.94	3637....	2.750	−20.07	−21.99
1620....	6.173	−19.76	−21.80	2529....	3.954	−19.92	−21.94	3657....	2.734	−20.06	−21.98
1630....	6.135	−19.73	−21.36	2550....	3.922	−19.92	−22.13	3677....	2.719	−20.06	−21.96
1640....	6.098	−19.69	−20.97	2571....	3.889	−19.92	−22.13	3700....	2.703	−20.07	...
1650....	6.061	−19.71	−21.26	2592....	3.858	−19.93	−22.09	3720....	2.688	−20.08	...
1660....	6.024	−19.72	−21.71	2613....	3.827	−19.93	−22.08				
1670....	5.988	−19.71	−21.90	2634....	3.796	−19.94	−22.06				
1680....	5.952	−19.71	−21.92	2655....	3.766	−19.95	−22.04				
1690....	5.917	−19.71	−21.97	2676....	3.737	−19.95	−22.04				

less reliable than the scanner data. Finally, for HD 50896 there is a discrepancy between the ground-based photometry and the OAO-2 photometry in the vicinity of 3 μm^{-1}. Code and Meade (1976) point out that the SP1 data for HD 50896 may be contaminated by light from HD 51733, an F-type star. If this contamination is present, its effects would be difficult to determine precisely. The most prominent effect would be to increase the measured intensity longward of 3.3 μm^{-1}. Thus, the presence of contamination would explain the

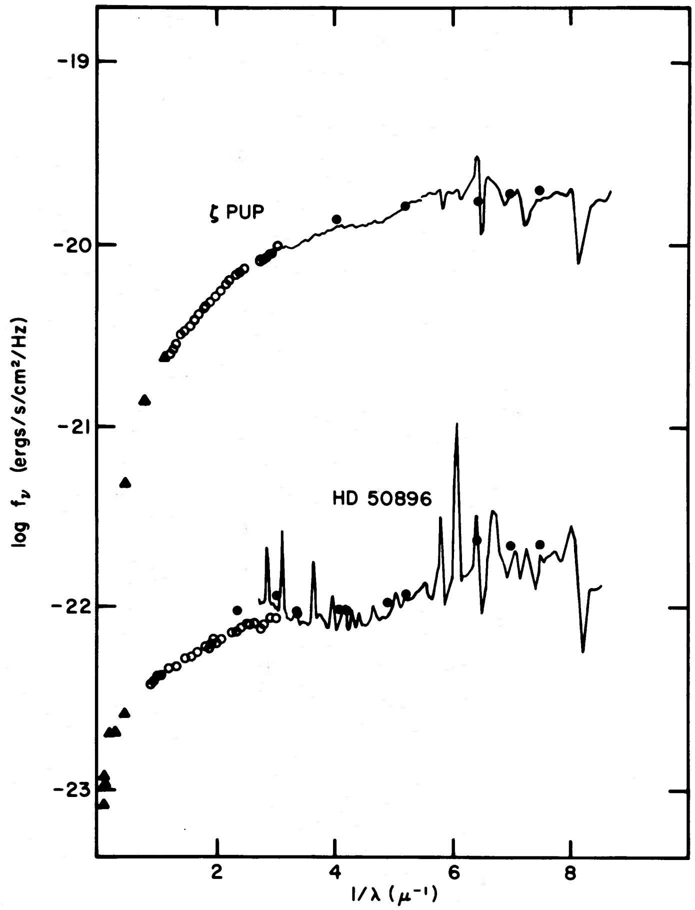

FIG. 1.—The observed energy distributions of ζ Pup and HD 50896. The fluxes have not been corrected for extinction. Fluxes derived from OAO-2 filter photometry are represented by filled circles; from visual scans, by open circles; and from infrared filter photometry, by filled triangles.

discrepancy found here between the observations of Kuhi and our observations. In addition, it would help to explain the discrepancy found by Smith (1972) between equivalent widths determined from ground-based spectrograms and those determined from OAO-2 spectrophotometry. However, in the ultraviolet we find moderately good agreement between fluxes from OAO-2 filter photometry and from SP1. Furthermore, we find no evidence for a strong absorption feature near 4.6 μm^{-1} that would be caused by the Mg II λ2800 absorption feature in the spectrum of HD 51733. Therefore, we believe that the effects on the derived energy distribution of the possible contamination are small in the ultraviolet. Nonetheless, we must accept the possibility that there is some contamination, which could reduce the accuracy of our determination of $E(B-V)$ for HD 50896 in the next section.

III. ENERGY DISTRIBUTIONS

In this section we intend to derive the intrinsic relative energy distribution for these stars and to compare that energy distribution with the results of model atmosphere calculations. But it is necessary first to consider the corrections to be made for interstellar extinction. It is clear from the work of Bless and Savage (1972) that these corrections are very important in the derivation of intrinsic stellar ultraviolet fluxes. The large values for $E(\lambda-V)/E(B-V)$ in the ultraviolet mean that a small error in $E(B-V)$ will cause a large error in the derived fluxes. Therefore we will be concerned with determining accurately $E(B-V)$ for both stars. Furthermore, Bless and Savage found that, while the extinction curves derived from most stars are nearly the same, there are stars for which the extinction curves differ greatly from the mean. We shall consider later the errors likely to arise from the use of an inappropriate extinction curve.

The measured $B-V$ of ζ Pup indicates that $E(B-V)$ will be small for this star. If we assume this star has an intrinsic $B-V$ appropriate for an O5 star (Johnson 1963), then we find $E(B-V) = 0.04 \pm (0.02, 0.01)$ from the colors collected in Blanco *et al.* (1968). This is the value of $E(B-V)$ used by Code *et al.* (1976) to derive $T_{\text{eff}} = 32{,}500$ K for ζ Pup.

The conclusions of Smith and Kuhi (1970) concerning the intrinsic colors of Wolf-Rayet stars imply that HD 50896 is completely unreddened. This apparent

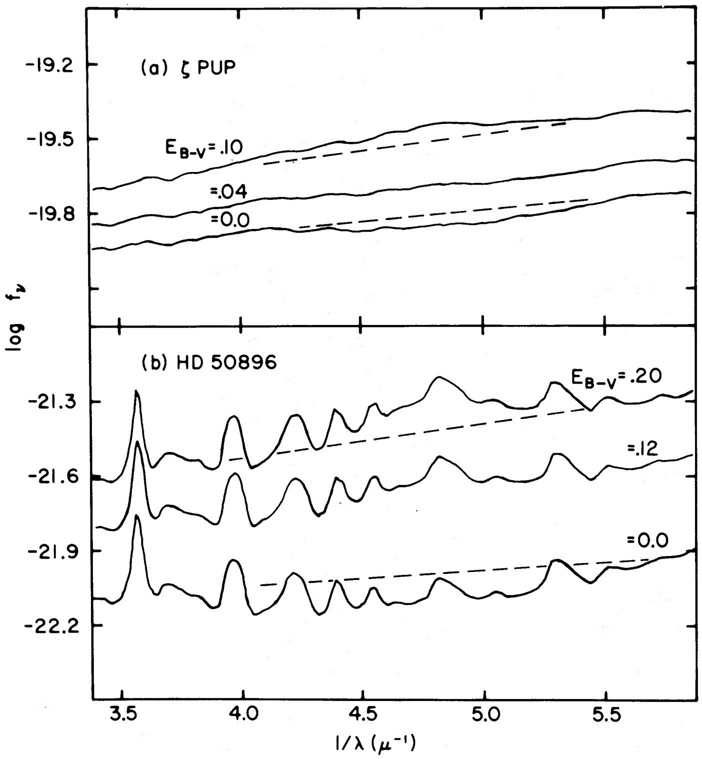

FIG. 2.—The energy distributions of (*a*) ζ Pup and (*b*) HD 50896 in the spectral range 3.5 μm^{-1} to 5.5 μm^{-1} with too little, optimum, and too much correction for extinction. Too little correction leaves a broad absorption centered on 4.6 μm^{-1}, while too much correction produces an apparent "emission" feature there. The mean extinction curve of Code *et al.* 1976 was used.

absence of extinction seems unlikely for a star located about 1.5 kpc from the Sun at a galactic latitude of only −10°. From the reddening of bright early B-type stars in the vicinity of HD 50896 we expect its $E(B-V)$ to be 0.17 ± 0.08. Determining the color excess of a star from relatively distant neighbors and foreground stars is risky because of inhomogeneities in the interstellar medium. Therefore new evidence is required to resolve the problem of the extinction of HD 50896.

An independent and powerful method for determining the extinction for stars whose intrinsic colors are not known is provided by the maximum in the interstellar extinction curve at $\lambda^{-1} = 4.6\ \mu m^{-1}$. Savage (1975) has found that, with few exceptions, the strength of this absorption feature correlates well with $E(B-V)$, Furthermore, the relative narrow width and great strength, $E(4.6-V)/E(B-V)$, of this feature make it comparatively easy to measure. Thus, by determining the extinction at 4.6 μm^{-1}, we can determine $E(B-V)$ quite accurately. We determined the extinction at 4.6 μm^{-1} by plotting the stellar energy distribution in the range 3.5 μm^{-1} to 5.5 μm^{-1} after correction for a series of assumed values of $E(B-V)$ using the mean extinction curve of Code *et al.* (1976). An inaccurate correction for extinction will result in an apparent broad "absorption" or "emission" feature centered on 4.6 μm^{-1}. In Figure 2*a*, we show the appearance of the energy distribution of ζ Pup after correction for assumed values of $E(B-V)$ of 0.0, 0.04, and 0.10 mag. It is clear that the choice of $E(B-V) = 0.0$ results in a broad "absorption" from 4.2 μm^{-1} to 5.5 μm^{-1}; we have undercorrected for extinction. The choice of $E(B-V) = 0.10$ results in a broad "emission" from 4.0 μm to 5.3 μm^{-1}; we have overcorrected for extinction. The choice of $E(B-V) = 0.04$ results in an energy distribution with a smooth slope. We have determined that the best fit for this spectral region is obtained with $E(B-V) = 0.04 \pm 0.02$. This result agrees well with that obtained from $B-V$ photometry.

By the same technique we find $E(B-V) = 0.12 \pm 0.06$ for HD 50896 (Fig. 2*b*). The relatively low signal-to-noise ratio and the possible presence of unresolved He II emission lines near 4.6 μm^{-1} make this determination less secure than that for ζ Pup. Nonetheless, this number is roughly in agreement with the number we derived from field stars and we shall use it as the best available.

Baschek and Sholz (1971) have suggested that the visual extinction of ζ Pup has been underestimated and that the extinction curve of θ Ori with its large R might be appropriate. To evaluate this suggestion, we have corrected ζ Pup for extinction, using the extinction curve derived from θ Ori as well as the mean curve. The results are illustrated in Figure 3. If $E(B-V) = 0.04$ is used with the θ Ori extinction curve, the derived flux is high in the visual because of the large value of R. However, in the ultraviolet this extinction curve results

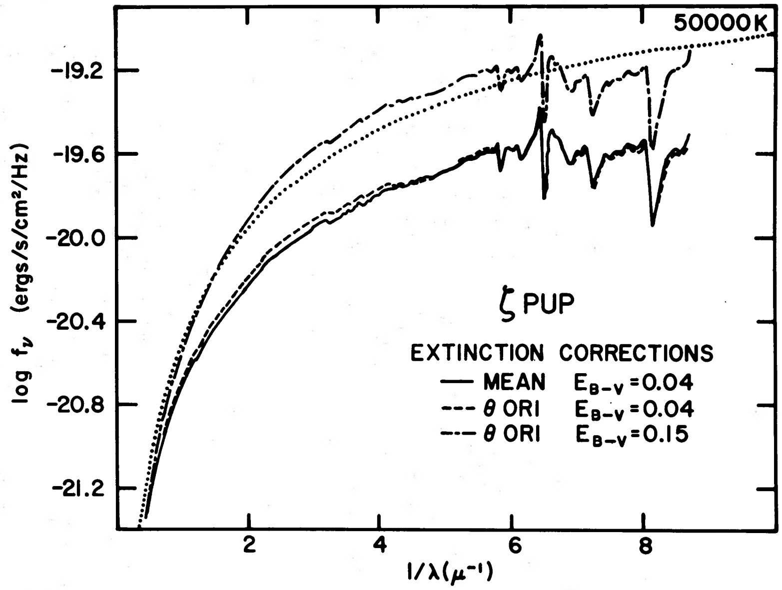

FIG. 3.—The energy distribution of ζ Pup corrected for extinction using the mean extinction curve with $E(B-V) = 0.04$ and the θ Ori extinction curve with $E(B-V) = 0.04$ and 0.15. The flux from a 50,000 K plane-parallel model atmosphere (Kurucz, Peytremann, and Avrett 1974) scaled to the observed angular diameter (Hanbury Brown, Davis, and Allen 1974) is shown for comparison. The use of the θ Ori extinction curve does not greatly increase the overall level of flux unless an unreasonably large color excess is assumed. Furthermore, the use of the θ Ori extinction curve with $E(B-V) = 0.04$ does not eliminate the extinction feature at 4.6 μm^{-1}.

in an energy distribution that lies below the one derived using the mean extinction curve. Moreover, this correction for extinction does not eliminate the dip in the energy distribution near 4.6 μm^{-1}. A correction for extinction using the θ Ori extinction curve and $E(B-V) = 0.15$ does eliminate the 4.6 μm^{-1} dip and brings the flux up to the level expected for a 50,000 K plane-parallel atmosphere, but it also results in a peculiar energy distribution that is very steep in the red and visual and nearly constant in the far-ultraviolet. While the peculiar shape of this energy distribution does not disprove the appropriateness of the θ Ori extinction curve as applied to ζ Pup, we feel that this extinction curve tends to create more problems than it solves. The mean extinction curve probably best describes the extinction of ζ Pup and will be used through the rest of the discussion.

Figure 4 shows the derived intrinsic energy distribution of ζ Pup. The emergent flux, $\mathscr{F}_\nu$, at the stellar surface has been calculated with the apparent angular diameter measured by Hanbury Brown, Davis, and Allen (1974). The quoted uncertainty in the angular diameter results in an uncertainty in the logarithm of the emergent flux of +0.03. The potential error in these results is increased by the uncertainty in the instrumental calibration. Since the calibration uncertainty increases toward shorter wavelengths (Bless, Code, and Fairchild 1976), it produces a potential error in the relative flux distribution as well as in the absolute level. Code *et al.* (1976) assume an uncertainty in the calibration at 1300 Å of 30%. This results in an uncertainty in the logarithm of the relative flux distribution between 7.7 μm^{-1} and the V-band of 0.11.

For comparison we have included, in Figure 4, the emergent fluxes of a plane-parallel model atmosphere of effective temperature 50,000 K from Kurucz, Peytremann, and Avrett (1974, hereafter KPA). It is clear that the unmodified flux of the 50,000 K model is too high. Heap (1972) noted that the energy distribution of ζ Pup could be fitted by a 50,000 K model if the model were calculated including the effects of geometrical extension. Similar conclusions were reached by Castor (1974) and Mihalas and Hummer (1974). Castor pointed out, however, that one must take special care in plotting the "surface" fluxes from extended atmosphere models. One must define the radius of the surface of the star in a way that is consistent with the interferometer response function. He defines the "effective radius" of a star as the radius of a uniform disk at the distance of the star that best fits the observed interferometer response function (cf. Cassinelli and Hoffman 1975). Heap (1972) apparently used the radius at the outer boundary of the model. Such an overestimate of the radius decreases the computed surface flux and flattens the energy distribution on a flux, $\mathscr{F}_\nu$, versus frequency plot. Electron scattering in a strong stellar wind can increase the radius as determined by an interferometer because of a halo effect (CAK; Cassinelli and Hoffman 1975). Therefore the absolute flux is not useful for determining whether extended continuum-formation regions are important. CAK thus concentrated on fitting the relative energy distribution of ζ Pup and found that a plane-parallel model gave a satisfactory fit in the visual region. Such a comparison can be extended now that we have good data in the ultraviolet. In the spirit of the CAK

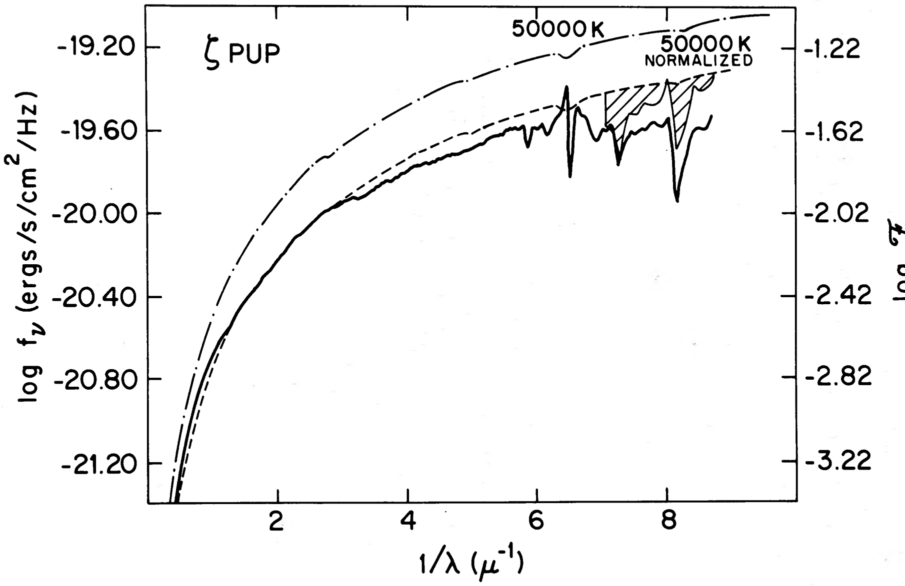

FIG. 4.—The energy distribution of ζ Pup corrected for $E(B-V) = 0.04$ with the mean extinction curve. The angular diameter (Hanbury Brown, Davis, and Allen 1974) was used to determine log $\mathscr{F}_\nu$, the intrinsic stellar surface flux. For comparison, the flux from a 50,000 K, log g of 4.5 plane-parallel model atmosphere (Kurucz, Peytremann, and Avrett 1974) is shown. We also show the flux from this model after two adjustments made to approximate the appearance of a strong stellar wind model (Castor, Abbott, and Klein 1975). A 33% increase in the effective radius by the halo effect has been assumed to normalize the model flux to the observed flux at 2.257 μm^{-1}. An empirical correction for line blocking (illustrated by the hatched area) from high-resolution *Copernicus* scans is used to allow for the effects of line blanketing in an expanding envelope. Further explanations and discussions are given in the text.

theory, we will make two adjustments to the plane-parallel model atmosphere results. First, as mentioned above, the apparent angular diameter of the star is affected by scattering in the flow region. Therefore we will allow the model's flux at 4430 Å to be adjusted to fit the observed data. The decrease in surface flux will give us information on the amount of material causing the halo effect. In the model of CAK, the flow speed increases rapidly with height above the photosphere. Thus there is an abrupt transition from the photospheric density distribution to the $1/r^2$ distribution in the flow region. In the empirical model of ζ Pup of Lamers and Morton (1976), derived from fits to P Cyg line profiles, the velocity rise is less rapid. This means the density in the region 1.0 to 1.5 stellar radii is larger, for a given mass loss rate, than the CAK model. This increases slightly the efficiency of the halo effect by increasing the optical thickness of the envelope.

The second adjustment we will allow in our comparison of model results with the observed energy distribution is an additional correction for line blanketing. While the KPA models are line-blanketed, CAK point out that line blanketing is very much greater in expanding atmospheres than in static atmospheres, because the expansion desaturates the strong lines. The desaturation permits moderately strong lines to create a large ultraviolet deficiency; the energy removed from the radiation field is assumed to be converted efficiently into the radial expansion of the envelope. There are no published models which include line blanketing with such great strength. Furthermore, the theoretical line blanketing is probably very model-dependent. Therefore we have chosen to estimate the blanketing for ζ Pup empirically from high-resolution *Copernicus* data (Morton and Underhill 1977), in the spectral range 7 μm^{-1} to 8.7 μm^{-1} and to apply the empirical blanketing correction to the surface fluxes of a plane-parallel model. We recognize that additional line blanketing may alter the structure of the atmosphere; we will discuss this problem below. The empirical line-blocking factors, smoothed over 10 Å bands, are given in Table 3. We note that these factors are highly dependent on the location of the assumed continuum, which, in this work, is taken to be a straight line connecting peaks in the spectrum. If the peaks do not reach the continuum, line blanketing will be underestimated.

Figure 4 shows the results of our two corrections applied to the flux of the 50,000 K KPA model. The observed absolute flux at 2.257 μm^{-1} (4430 Å) can be fitted if we reduce the model flux by 0.57 ± 0.09. This leads to an excellent fit throughout the optical to 1.25 μm^{-1}. Such a reduction corresponds to an increase in effective radius by the halo effect of 33 ± 9%. This is possible with flows having mass loss rates of order 10^{-5} $M_\odot$ per year. The model fluxes are still about 23% high in the ultraviolet. A better fit results if we consider a KPA model with $T_{\rm eff}$ of 42,000 K. The decrease of $T_{\rm eff}$ from 50,000 K to 42,000 K is within the range of the spectroscopic temperature estimates of Baschek and Scholz. This model requires a halo correction to the flux at 2.257 μm^{-1} of 0.68 ±

TABLE 3

EMPIRICAL LINE-BLANKETING FACTORS

$1/\lambda$ (μm^{-1})	$\mathscr{F}/\mathscr{F}_c$	$\log \mathscr{F}/\mathscr{F}_c$
7.04..........	0.70	−0.16
7.14..........	0.67	−0.18
7.25..........	0.50	−0.30
7.41..........	0.75	−0.12
7.52..........	0.74	−0.13
7.63..........	0.83	−0.08
7.75..........	0.80	−0.10
7.87..........	0.82	−0.09
8.00..........	1.05	+0.02
8.13..........	0.47	−0.32
8.26..........	0.67*	−0.18*
8.40..........	0.92	−0.04
8.55..........	0.86	−0.07
8.70..........	0.93	−0.03

* Includes interstellar Lα.

0.10, which corresponds to an increase of 21 ± 9% in the effective radius. The corrected 42,000 K model lies only 11% above the observed energy distribution in the far-ultraviolet. This difference is approximately the uncertainty in the absolute calibration of the OAO in the far-ultraviolet (Bless, Code, and Fairchild 1976). Therefore, if we push both the spectroscopic $T_{\rm eff}$ and the ultraviolet calibration to their limits, we can fit the observed ζ Pup energy distribution with a plane-parallel model adjusted for the CAK effects.

An additional constraint on the model taken to represent ζ Pup is imposed by the presence of the Gum nebula: a sufficient number of extreme-ultraviolet photons must be radiated to maintain the ionization of the nebula. Reynolds (1976) estimates that (7.5 ± 4.0) × 10^{49} photons s^{-1} capable of ionizing hydrogen are required to maintain the ionization of the nebula. In addition to ζ Pup, the Wolf-Rayet binary γ^2 Vel lies within the nebula and helps to maintain the ionization. We estimate that γ^2 Vel provides from 0.2 × 10^{49} to 1.8 × 10^{49} ionizing photons s^{-1} on the basis of the effective temperature of the O9 I component (Code *et al.* 1976) and the Zanstra temperature of a WC5 star (Morton 1969). Therefore, we find that ζ Pup must provide at least 1.7 × 10^{49} ionizing photons s^{-1}. If we take the distance to the star to be 400 pc and scale the models to the *V*-magnitude, we find the 50,000 K model produces 6.4 × 10^{49} ionizing photons s^{-1}, the 45,000 K model produces 4.0 × 10^{49} ionizing photons s^{-1}, and the CAK flow model produces 6.7 × 10^{49} ionizing photons s^{-1}. These models are all acceptable. A star having an effective temperature of 35,000 K or less would be unable to produce the minimum number of ionizing photons required to maintain the ionization of the nebula.

Thus we have found that the observed energy distribution of ζ Pup can be explained without an appeal to models having extended continuum-formation regions. Mihalas (1974), Castor (1974), and Cassinelli and Hartmann (1975) have found, in fact, that it is difficult to extend the optical continuum-formation regions of massive stars by radiation pressure effects. However, in order to fit the observations, we have had to assume an electron-scattering envelope that increases the effective radius by 21 to 33% and to adjust the model fluxes for line blanketing that removes about 50% of the radiated energy. The increase in effective radius corresponds to an electron-scattering envelope with an optical thickness in the continuum of about one-third. CAK report having constructed a model with such a thick envelope for which the relative energy distribution was the same as that of a static model. However, CAK do not include line blanketing. Line blanketing greatly increases the total opacity of the envelope in the spectral regions where the photosphere radiates most flux. It does not seem plausible that nearly 50% of the stellar flux can be scattered back to the photosphere without producing some change in the energy distribution. Thus, it is clear that new model atmospheres with greatly increased line blanketing are required to fit the observations.

Figure 5 shows the derived intrinsic energy distribution of HD 50896. Since there is no measurement of the angular diameter of this star, we have not shown an absolute emergent flux. To compare the observations with theory, we have normalized two model atmospheres to the observed flux at 1.8 μm^{-1}. The 50,000 K plane-parallel model of KPA is steeper than the observed energy distribution at all frequencies. The extended atmosphere model for a Wolf-Rayet star by Cassinelli and Hartmann (1975) does represent the observed distribution moderately well over a wide range of frequencies, although it was not constructed specifically to represent this star. For example, the model atmosphere was constructed with normal abundances, while Smith (1972) has determined that HD 50896 is very hydrogen-deficient. Thus it will not be surprising to find some differences between the model and the observations.

There is a large infrared excess in the star which has been discussed by Cassinelli and Hartmann (1975). Another flux excess occurs in the ultraviolet between 7 μm^{-1} and 8 μm^{-1}. We have several arguments that this flux excess is not intrinsic to the star but is an artifact of the data reduction and of the instrumental resolution. First, in this spectral region the observed interstellar extinction curves tend to diverge (Bless and Savage 1972). Therefore, if the extinction for this star is not represented exactly by the mean curve, the errors will be greatest here. The apparent excess could be because the true extinction at higher frequencies than 7 μm^{-1} is less than the mean. Second, as discussed above, the uncertainty in the calibration in this region is about 30%. A change in that amount is adequate to bring the apparent flux into agreement with the model. Finally, in this spectral region there may be emission lines of O IV, O V, Si IV, and other ions which would be at best only partially detectable with the OAO-2 resolution. If so, the continuum would be below the observed energy distribution and, in fact, might be well represented by the extended atmosphere W-R model.

The cause of such an extension is uncertain. The extended subsonic atmosphere model of Cassinelli and Hartmann required the luminosity to be very near the

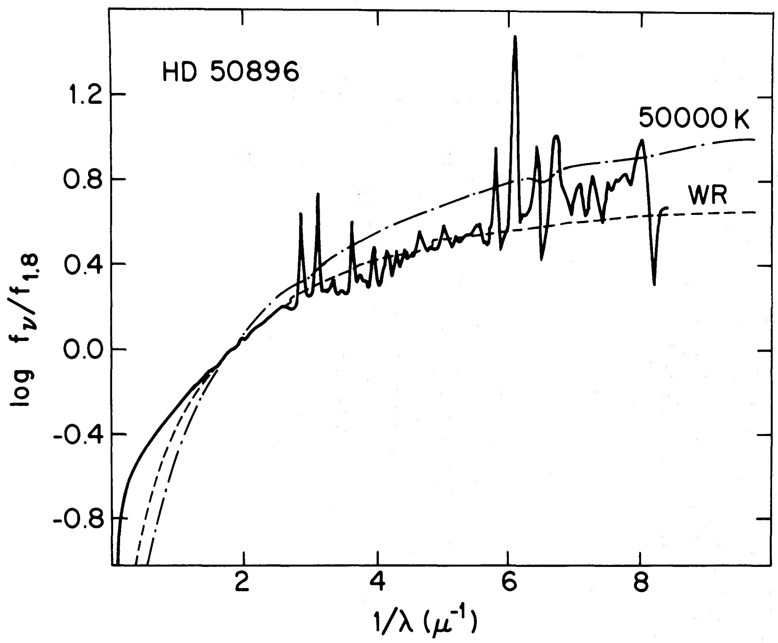

FIG. 5.—The energy distribution of HD 50896 after correction for $E(B-V) = 0.12$. For comparison the relative energy distribution of a 50,000 K, log g of 4.5 plane-parallel model atmosphere (Kurucz, Peytremann, and Avrett 1974) and of a Wolf-Rayet model atmosphere (Cassinelli and Hartmann 1975) are shown. The energy distributions of both models have been normalized to the observed stellar flux at 1.8 μm^{-1}.

Eddington luminosity limit. An alternative explanation of the extension is that the star has an optically thick supersonic wind. The difficulties in producing such a flow are appreciable.

The agreement between the model and observed energy distributions does not provide an effective temperature for HD 50896, since a hotter star with a more extended atmosphere would have the same relative energy distribution (Cassinelli 1971*a*).

IV. CONCLUSIONS

We have determined the ultraviolet energy distribution of ζ Pup and HD 50896 using the absolute calibration of Bless, Code, and Fairchild (1976). From the size of the interstellar extinction bump at 4.6 μm^{-1}, we have estimated $E(B-V) = 0.04$ for ζ Pup and $E(B-V) = 0.12 \pm 0.06$ for HD 50896. We find the intrinsic energy distribution for both stars to be anomalously flat when compared with fluxes calculated using plane-parallel atmosphere theory. This result confirms the conclusions of earlier authors (e.g., Kuhi 1966; Heap 1972). This result is in apparent agreement with the extended continuum-formation region models of Cassinelli (1971*a*, *b*), Kunasz, Hummer, and Mihalas (1975), and Cassinelli and Hartmann (1975). However, the energy distribution of ζ Pup can also be explained by a stellar wind model (Castor, Abbott, and Klein 1975), if the envelope can be made relatively thick ($\tau \geq 0.3$).

We have found that, within the possible errors, the observed Wolf-Rayet energy distribution agrees with the W-R model. This conclusion is weakened, since the HD 50896 fluxes are of lower quality than the ζ Pup fluxes, because of the relatively greater importance of skylight and because of the extinction correction. Nonetheless, it appears that the high helium abundance of this WN star does not result in an extremely large ultraviolet excess such as found by van der Hucht (1975) for γ^2 Vel, a WC star and a spectroscopic binary.

Our work suggests that there is a need for stellar wind models that include line-blanketing opacity sources and for helium-rich extended atmosphere models. A very important observational problem involves reducing the uncertainty in the ultraviolet calibration at frequencies higher than 7 μm^{-1}. Other observational problems include the determination of the infrared energy distribution of ζ Pup, near-infrared spectroscopy of HD 50896 to test for the presence of a cool secondary (Kuhi 1966), and high-resolution ultraviolet spectroscopy of HD 50896 at 4 to 5 μm^{-1} and to 6 to 8 μm^{-1} to determine the degree to which unresolved emission lines affected our choice of continuum.

We thank Arthur Code, Lee Hartmann, and Henny Lamers for helpful discussions, and Karel van der Hucht for comments on a manuscript version of this work. We thank Don Morton and Anne Underhill for permitting us to use *Copernicus* scans of ζ Pup in advance of publication and Lindsay Smith for providing an atlas of Wolf-Rayet spectra. We thank Marilyn Meade for her assistance in processing the OAO-2 scanner data. This work was supported in part by NASA NSG-7050 and NSF grant MP74-01489.

REFERENCES

Arvesen, J. C., Griffin, R. N., and Pearson, B. D. 1969, *Appl. Optics*, **8**, 2215.
Barbon, R., Bertola, F., Ciatti, F., and Margoni, R. 1965, *IAU Infor. Bull. Var. Stars*, No. 109.
Baschek, B., and Scholz, M. 1971, *Astr. Ap.*, **15**, 285.
Blanco, V. M., Demers, S., Douglass, G. G., and Fitz-Gerald, M. P. 1968, *Pub. US Naval Obs.*, Ser. 2, No. 21.
Bless, R. C., Code, A. D., and Fairchild, E. T. 1976, *Ap. J.*, **203**, 410.
Bless, R. C., and Savage, B. D. 1972, *Ap. J.*, **171**, 293.
Cassinelli, J. P. 1971*a*, *Ap. Letters*, **8**, 105.
———. 1971*b*. *Ap. J.*, **165**, 265.
Cassinelli, J. P., and Haisch, B. M. 1974, *Ap. J.*, **188**, 101.
Cassinelli, J. P., and Hartmann, L. 1975, *Ap. J.*, **202**, 718.
Cassinelli, J. P., and Hoffman, N. 1975, *M.N.R.A.S.*, **173**, 789.
Castor, J. I. 1974, *Ap. J.*, **189**, 273.
Castor, J. I., Abbott, D. C., and Klein, R. I. 1975, *Ap. J.*, **195**, 157 (CAK).
Code, A. D. 1973, in *IAU Symposium No. 54, Problems of Calibration of Absolute Magnitudes and Temperatures of Stars*, ed. B. Hauck and B. E. Westerlund (Boston: Reidel), p. 131.
———. 1975, private communication.
Code, A. D., Davis, J., Bless, R. C., and Hanbury Brown, R. 1976, *Ap. J.*, **203**, 417.
Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F. 1970, *Ap. J.*, **161**, 377.
Code, A. D., and Meade, M. R. 1976, *Wisconsin Ap.*, No. 30.
Conti, P. S. 1973, *Ap. J.*, **179**, 181.
Davis, J., Morton, D. C., Allen, L. R., and Hanbury Brown, R. 1970, *M.N.R.A.S.*, **150**, 45.
Davis, J., and Webb, R. J. 1973, *M.N.R.A.S.*, **168**, 163.
Doherty, L. R. 1972, *Ap. J.*, **178**, 727.
Gallagher, J. S. 1972, Ph.D. thesis, University of Wisconsin.
Gehrz, R. D., and Hackwell, J. A. 1974, *Ap. J.*, **194**, 619.
Gehrz, R. D., Hackwell, J. A., and Jones, T. W. 1974, *Ap. J.*, **191**, 675.
Hanbury Brown, R., Davis, J., and Allen, L. R. 1974, *M.N.R.A.S.*, **167**, 121.
Hayes, D. S., and Latham, D. W. 1975, *Ap. J.*, **197**, 593.
Heap, S. R. 1972, *Ap. Letters*, **10**, 49.
Hiltner, W. A., and Schild, R. E. 1966, *Ap. J.*, **143**, 770.
Holm, A. V., and Meade, M. R. 1976, *Wisconsin Ap.*, No. 29.
Johnson, H. L. 1963, in *Stars and Stellar Systems*, Vol. **3**, *Basic Astronomical Data*, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 204.
———. 1964, *Bol. Obs. Tonantzintla y Tacubaya*, **3**, 305.
Johnson, H. L., Mitchell, R. I., Iriarte, B., and Wisniewski, W. Z. 1966, *Comm. Lunar Planet. Lab.*, **4**, 99.
Kuhi, L. V. 1966, *Ap. J.*, **143**, 753.
———. 1967, *Pub. A.S.P.*, **79**, 57.
Kunasz, P. B., Hummer, D. G., and Mihalas, D. 1975, *Ap. J.*, **202**, 92.
Kurucz, R. L., Peytremann, E., and Avrett, E. H. 1974, *Blanketed Model Atmospheres for Early Type Stars* (Washington: Smithsonian Institution Press) (KPA).
Labs, D., and Neckel, H. 1968, *Zs. f. Ap.*, **69**, 1.
Lamers, H. J. G. L. M., and Morton, D. C. 1976, in preparation.
Leckrone, D. S. 1973, *Ap. J.*, **185**, 577.
Lucy, L. B., and Solomon, P. 1970, *Ap. J.*, **159**, 879.
Mihalas, D. 1974, *A.J.*, **79**, 1111.
Mihalas, D., and Hummer, D. G. 1974, *Ap. J.* (*Letters*), **189**, L39.
Moffatt, A. F. J., and Haupt, W. 1974, *Astr. Ap.*, **32**, 435.
Morton, D. C. 1969, *Ap. J.*, **158**, 629.
Morton, D. C., and Underhill, A. B. 1977, in preparation.
Navach, C., and Meade, M. R. 1976, *Wisconsin Ap.*, No. 28.
Pyper, D. M. 1966, *Ap. J.*, **144**, 13.
Reynolds, R. J. 1976, *Ap. J.*, **203**, 151.
Savage, B. D. 1975, *Ap. J.*, **199**, 92.
Schmidt, G. D. 1974, *Pub. A.S.P.*, **86**, 767.
Serkowski, K. 1970, *Ap. J.*, **160**, 1083.
Smith, L. F. 1968, *M.N.R.A.S.*, **141**, 317.
———. 1972, in *Scientific Results from the Orbiting Astronomical Observatory* (*OAO-2*), ed. A. D. Code (NASA SP-310), p. 429.
Smith, L. F., and Kuhi, L. V. 1970, *Ap. J.*, **162**, 535.
Van Blerkom, D., and Patton, G. 1972, *Ap. J.*, **177**, 547.
van der Hucht, K. A. 1975, *Phil. Trans. Roy. Soc. London*, A **279**, 451.
Walborn, N. R. 1974, *Ap. J.*, **189**, 269.
Wilson, O. C. 1948, *Pub. A.S.P.*, **60**, 383.

JOSEPH P. CASSINELLI: Department of Astronomy, University of Wisconsin, Madison, WI 53706

ALBERT V. HOLM: Space Astronomy Laboratory, University of Wisconsin, Madison, WI 53706