ROCKET SPECTROSCOPY OF ζ PUPPIS BELOW 1100 Å

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Abstract. A spectrum of ζ Pup extending from 920 Å to 1360 Å with approximately 0.8 Å resolution has been recorded at rocket altitudes. Tentative identification of 38 multiplets below 1100 Å has been made from which it is concluded that all the lines appearing in a model atmosphere (Hickok and Morton, 1968) with $T_e = 37450$K have been detected with the exception of those masked by telluric N_2 or strong P Cygni-like profiles. Additional absorption lines indicate a wide range of ionization and excitation entirely consistent with observations in the visible spectral region of similar type stars; they also appear to affect sensibly the energy distribution within the spectrum. From newly detected blue-shifted absorption features produced by the ions S VI (933.4 Å, 944.5 Å), N IV (955.3 Å), N III (991.0 Å), and O VI (1033.8 Å) mean radial velocities of 1200, 530, 1800 and 1900 km sec^{-1} respectively have been derived. It is pointed out that the transition in N IV (955.3 Å) does not originate in the ground state configuration as do the other P Cygni profile transitions, but from an excited level which can decay radiatively to the ground state. It seems likely, therefore, that the profile is generated close to the photosphere, and this, together with previously reported results, constitutes evidence for a positive velocity gradient in the detected portion of the circumstellar envelope. On the basis of available data, ions in the ground state of N V, N IV (by inference) and N III are all present in the circumstellar envelope, the abundance of the latter remaining large enough to produce a strong P Cygni profile.

1. Introduction

In recent years the star ζ Pup (O5 f) has come under close spectroscopic scrutiny in the rocket ultraviolet due in part to interest in its intrinsic physical characteristics and in part to the fact that it is one of the few nearby hot objects accessible to small aperture instruments. Some of the results are dramatic. For example, the observations of Carruthers (1968), Stecher (1968), and Morton *et al.* (1969) have revealed strong blue shifted absorption features accompanied by emission at the long wavelength edges similar to P Cygni profiles. The chief distinction of these combined absorption-emission features in the case of ζ Pup is that the radial velocities calculated from the profiles are considerably larger than those normally associated with P Cygni stars. Thus, the ions C III, C IV, N V, and Si IV have all been observed with mean radial velocities exceeding 1500 km sec^{-1}, and the extrapolated maximum radial velocities are approximately twice this value. Bearing in mind that for reasonable values of stellar mass and radius the escape velocity at the surface of the star is near 1100 km sec^{-1}, the data indicate a continual loss of mass from ζ Pup, and the rate of mass loss becomes an interesting evolutionary question.

Regarding the model atmospheres appropriate to ζ Pup (Hickok and Morton, 1968; Bradley and Morton, 1969) we may also inquire as to whether the selected absorption lines are sufficient to calculate the effect of line blanketing on the distribution of energy in the optical spectrum. The observations thus far have indicated that the existing models are adequate in this respect. However, for a star of this type with an effective temperature estimated to be 48000 K (Morton, 1969) serious line-blanketing effects would be expected at wavelengths below 1100 Å, and this region has not

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as yet been studied. In any case the identification of weak unshifted lines can give a qualitative indication of the ionization and excitation in that part of the atmosphere with no detected residual radial motion.

A rocket observation of ζ Pup carried out in March, 1968 with a stigmatic mounting spectrograph has provided data extending the wavelength coverage of this star down to 920 Å. Several heretofore unobserved P Cygni-like profiles have been identified as have a number of weak, photospheric lines arising from excited levels in both abundant and relatively rare ions. In this report these data will be presented and discussed.

2. A Brief Experiment Description

A description of the instrument appears elsewhere (Smith, 1969); however, some of the salient features are presented here again. There is a single optical element namely, a concave grating ruled at 1200 lines mm^{-1} which defines an instrumental aperture of 14 cm^2. The focal length is about 25 cm, the linear dispersion is 33.4 Å mm^{-1}, and in flight the spectrograph provides approximately 0.8 Å resolution. The dimensions of the ζ Pup spectrogram were 13.5 mm in the dispersion plane by 0.13 mm normal to the dispersion plane. Kodak Pathé SC5 film was used, and was developed for 2 min in D19b according to the manufacturer's specifications. The rocket trajectory achieved an altitude of about 125 miles during which two exposures were made, one for 214 sec, the other for 68 sec.

The wavelength scale was determined by fitting the data to a quadratic function of position measured along the spectrogram with the bands of telluric N_2 (960 Å) and the interstellar lines of N I (1134.6 Å) and Si II (1304.4Å) serving as calibration points. The resulting scale is thought to be accurate to 0.3 Å.

3. Results

A reproduction of the two exposures with some of the more obvious lines indicated appears in Figure 1. The top spectrum, corresponding to the 68-sec exposure, suffered fogging from a light leak resulting from a launch–aggravated shutter malfunction. Nevertheless, it contains some useful data at wavelengths longer than 1200 Å. For the purposes of this report, however, attention is focussed on the spectrum below 1100 Å. Accordingly, Figure 2 contains a densitometer trace of the long exposure spectrogram from 910 Å to 1100 Å together with the tentative identifications of 28 multiplets. The Hickok and Morton theoretical spectrum for an atmosphere with $T_e = 37450$ K and $\log g = 4.00$ is exhibited over the recorded spectrum for comparison purposes.

In this particular wavelength region it is necessary to be aware of the effects of telluric N_2 absorption bands. The most important of these extend as indicated from approximately 950 Å to 992 Å strongly modifying the stellar spectrum at 960, 966, and 972 Å. It should also be noted that a strong resonance line due to interstellar C II at 1036 Å influences greatly a P Cygni-like profile in O VI near this same wavelength. A rather weak line at 1097 Å, attributed to interstellar Fe II, affects the stellar spectrum very

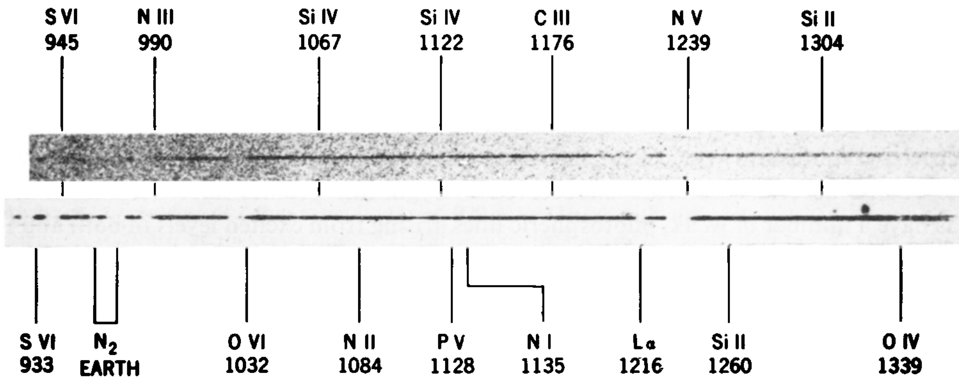

Fig. 1. Two spectrograms of ζ Pup. Exposure times of top and bottom spectrograms were 68 sec and 214 sec respectively. Some identifications of the stronger features are shown, the numbers indicating the approximate wavelengths in Å.

little. Water vapor evaporating from the rocket and payload probably accounts for the moderate sized feature at 1055 Å, and the feature at 1084.3 Å must be due partially to a resonant transition in N II (1083.98 Å) arising in the Strömgren sphere.

4. Discussion

Most of the bound-bound transitions used in the model can be identified with features appearing in the spectrogram; those for which no positive identification can be made occur in wavelength regions occupied either by N_2 absorption bands or strong P Cygni profiles. Some of the measured line strengths, however, may be vastly different from the model values. Such is the case for the S IV doublet at 1063 and 1074 Å. Also, the combined effects of H I and He II seem to be less than expected as is seen most clearly by the feature attributed at least in part to these absorbers at 950 Å.

There are weak lines in the observed spectrum, not included in the model, which reflect a wide range in ionization and excitation in the star's atmosphere. Included in this category are lines of N III, N IV, N V, Si III, Si IV, P III, P IV, P V, S III, S IV, Cl III, and Cl IV. Due to the ragged character of the spectrum the evidence for those transitions proceeding from excited states and revealed as weak lines is considered to be only mediocre. On the other hand, there is good evidence for ground state transitions in C III (977 Å), P IV (951 Å), S III (1012 Å), S IV (1063–74 Å), and Cl IV (973–86 Å). The identification of the resonance transitions in Cl III (1005–15 Å) is much less certain. The lines of C II (1036 Å) and Fe II (1097 Å) are probably interstellar in origin.

Table I presents the line identifications made in the spectrum for wavelengths between 923 Å and 1100 Å. Listed in column 1 is the ion identification, and directly under this the multiplet number found in either *An Ultraviolet Multiplet Table* or *Selected Tables of Atomic Spectra* both by Moore (1950, 1965). If a multiplet or line is not contained in this table two references of Kelly (n.d., 1968) signified by K1 and K2 respectively, are indicated. Columns 2, 3, 4 and 5 contain the laboratory measured

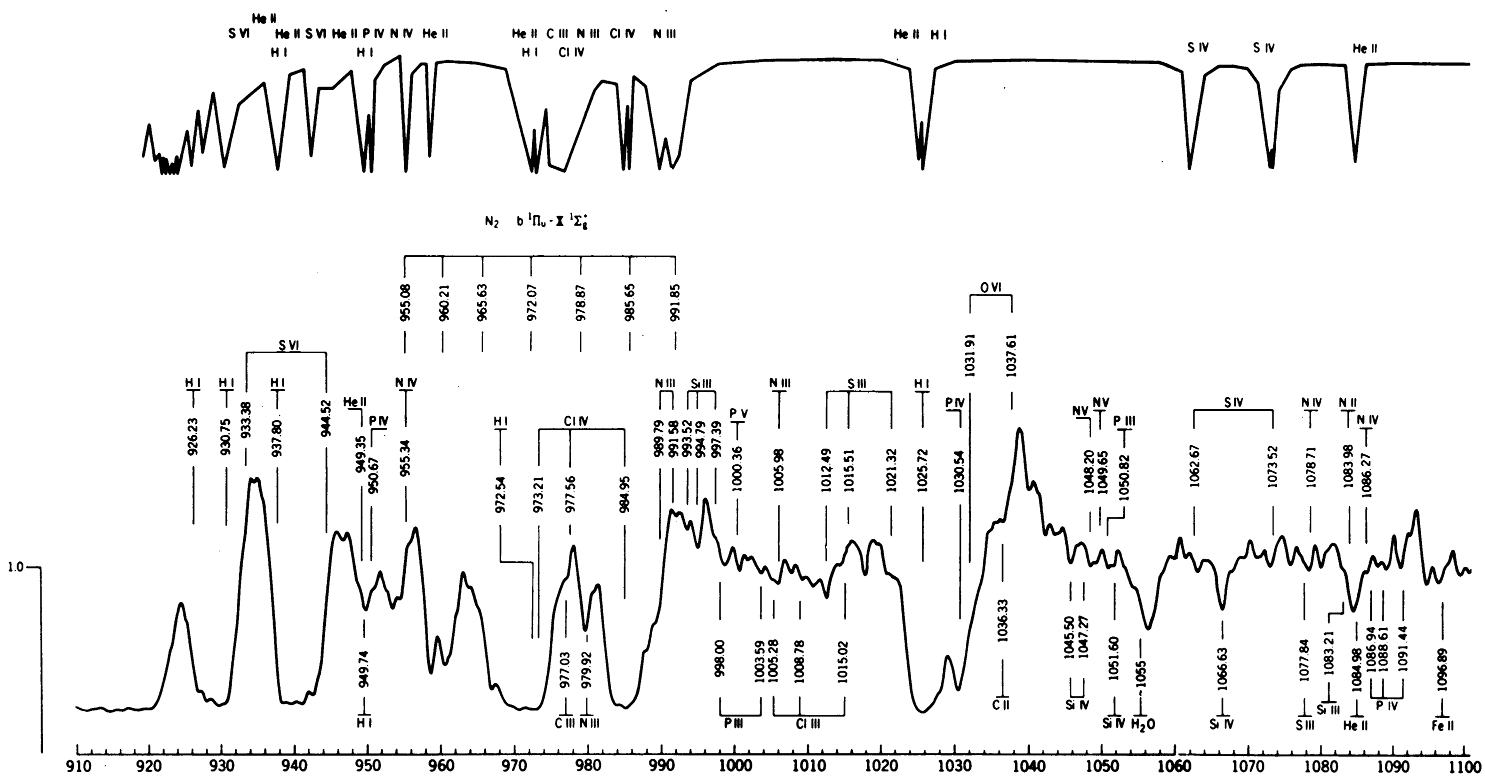

Fig. 2. Microdensitometer trace of the 214 sec exposure ζ Pup spectrogram. The abscissa is in Ångstrom units, the ordinate in density units. Drawn above the recorded spectrum is the model spectrum of Hickok and Morton (1968) in which the ordinate units are ergs $cm^{-2}\,sec^{-1}\,(Hz)^{-1}$. Vertical lines indicate transitions associated with various spectral features; horizontal lines connect members of the same multiplet.

TABLE I

Identification of lines in the UV spectrum of ζ Pup

Ion multiplet	Laboratory wavelength (Å)	Measured wavelength (Å)	χ(eV)	*gf*	Remarks
H I	949.74	949.9	0.00	0.02788	Moderate
UV (4)					
He II	949.30	949.9	40.64	0.030808	Weak; probable
UV (19)	949.35				
He II	1084.91	1084.3	40.64	0.35736	Moderate
UV (14)	1084.98				
C II	1036.33	1036.3	0.00	0.12	Weak; probable; interstellar
UV (2)					
C III	977.03	977	0.00	0.81	Weak; probable
UV (1)					
N II	1083.98		0.00	0.17	Moderate
UV (1)	1084.57		0.01	0.13	
	1084.57	1084.3	0.01	0.39	
	1085.54		0.02	0.12	
	1085.70		0.02	0.70	
N III	979.77		12.47	0.08	Weak; probable
UV (12)	979.84	979.7	12.47	0.72	
	979.92		12.47	1.12	
	980.01		12.47	0.08	
N III	989.79	985.0	0.00	0.36	Strong; P Cygni profile
UV (1)	991.51	990.3	0.02	0.07	
	991.58		0.02	0.65	
N III	1005.98	1005.9	16.17	0.36	Weak; probable
UV (17)	1006.03			0.18	
N IV	955.34	953.8	16.13	0.22	Moderate; P Cygni profile
UV (8)		955.3			
N IV	1078.71	1078.4	52.98	–	Weak; possible
K2					
N IV	1086.08		50.11	–	Very weak; possible
K2	1086.27	1086.3	50.12	-	
	1086.69		50.12	–	
N V	1048.20	1048.7	76.28	–	Weak; possible
K2					
N V	1049.65	1048.7	76.29	–	Weak; possible
K2					
O VI	1031.91	1025.3	0.00	0.26	Strong; P Cygni profile
UV (1)		30.3			
	1037.61	1034.2	0.00	0.13	
Si III	993.52	993.6	6.54	0.20	Weak; probable
UV (6)	994.79	994.8	6.55	0.64	
	997.39	997.3	6.58	1.00	
Si III	1083.21	1083.1	15.15	–	Very weak; possible
UV (23)					

Ion multiplet	Laboratory wavelength (Å)	Measured wavelength (Å)	χ(eV)	*gf*	Remarks
Si IV	1045.50	1045.8	27.06	–	Weak; possible
UV (21)	1047.27	1048.2	27.08	–	
Si IV	1051.60	1051.1	–	–	Weak; possible
K1					
Si IV	1066.63	1066.4	19.88	–	Moderate
UV (11)					
P III	998.00	998.7	0.00	–	Very weak; possible
UV (2)	1003.59	1003.6	0.07	–	
P III	1049.82		9.29	–	Weak; probable
K2	1050.52	1051.0	9.29	–	
	1050.82		9.29	–	
P IV	950.67	951.1	0.00	2.75	Weak; probable
UV (1)					
P IV	1025.58	–	8.41	–	Weak; possible
UV (2)	1028.13	–	8.38	–	
	1030.54	1030.3	8.47	–	
	1033.14	–	8.41	–	
	1035.54	–	8.47	–	
P IV	1086.94	1086.3	23.47	–	Very weak; possible
K2	1088.61	1089.0	23.47	–	
	1091.44	1091.0	23.47	–	
P V	997.64	997.3	25.31	–	Very weak; possible
K2	1000.36	1000.6	25.31	–	
S III	1012.49	1012.5	0.00	0.30	Weak; probable
UV (2)	1015.51	1014.5	0.04	0.52	
	1015.76		0.04	0.38	
	1021.10	1021.3	0.10	0.38	
	1021.32		0.10	1.12	
S III	1077.84	1078.4	1.40	–	Weak; possible
UV (8)					
S IV	1062.67	1063.0	0.00	0.94	Weak; probable
UV (1)	1072.99	1073.0	0.12	0.19	
	1073.52		0.12	1.69	
S VI	933.38	928.8	0.00	0.5	Strong; P Cygni profiles
UV (1)		933.0			
	944.52	940.8	0.00	1.0	
		945.2			
Cl III	1005.28	1005.0	0.00	0.56	Very weak; possible
UV (1)	1008.78	1009.2	0.00	1.10	
	1015.02	1014.5	0.00	1.66	
Cl IV	973.21		0.00	0.55	Weak; probable
K2	977.56	977.0	0.06	1.24	
	977.90		0.06	0.42	
	984.95		0.17	2.32	
	985.75		0.17	0.44	
Fe II	1096.89	1096.3	0.00	–	Weak; possible; interstellar
UV (18)					

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wavelength, the observed spectral feature wavelength, the excitation potential and the *gf* value respectively. In column 6 eye estimates of the magnitude of the observed spectral features are presented together with a certainty estimate of the identification. An interstellar line or P Cygni profile is also indicated in this column. In the case of the latter, two numbers are listed for each transition in column 3. The first is the wavelength at which the minimum residual intensity is found in the absorption feature; the second is the wavelength corresponding to the short wavelength edge of the emission feature. No blends were indicated as such because almost assuredly all observable features are blends of several transitions only some of which are known.

The recently detected P Cygni-like profiles occur for transitions in N III (991.0 Å), N IV (955.3 Å), O VI (1033.8 Å) and S VI (933.4, 944.5 Å). The mean radial velocities measured at the center of the blue shifted absorption feature and the extrapolated maximum radial velocities are listed in Table II.

TABLE II

Characteristic radial velocities of ions in the atmosphere of ζ Pup

Ion	N III	N IV	O VI	S VI
Central velocity (km sec^{-1})	1800	530 (780)	1900	1200
Extrapolated maximum velocity (km sec^{-1})	3300	1500	3500	2500

For the purposes of this table the appropriate velocities derived from each of the S VI line profiles have been averaged, and the contribution of the 985 Å line of Cl IV to the absorption component of the N III (991.0 Å) profile has been assumed negligible. The number appearing in parentheses is the mean velocity obtained by Morton *et al.* using a P Cygni profile in N IV found at 1719 Å. It is noteworthy that both the 955 Å and 1719 Å lines of N IV originate at the same excited level ($2p\ ^1P^0$, 16.13 eV) which can decay radiatively to the ground state ($2s^2\ ^1S$) with $gf=0.64$. The most likely way that the $^1P^0$ level can be populated is by ordinary thermal processes. This implies that the radiation field can not be significantly diluted, and that the N IV ions must therefore be close to the photosphere. Morton (1969) has also reached this conclusion.

The P IV line at 1031 Å originates at an 8.47 eV level, and is expected to affect the spectrum only weakly. Thus, the moderate absorption feature at this wavelength can be interpreted as the absorption component of the P Cygni profile associated with the 1037.6 Å line in O VI, whereas the strong absorption feature at 1025.5 Å should be associated with the 1031.9 Å line. If this is the case the absorption components of the doublet are partially resolved, and may provide a basis for a mass loss estimate.

5. Summary and Conclusions

All lines used in the Hickok and Morton model have been detected except for those either masked by N_2 absorption bands or by strong P Cygni-like profiles. Lines identified in addition to the model lines are weak but closely packed together, and they would affect the energy distribution in the spectrum if they were included in the model. This is particularly noticeable near 1010 Å.

The weak lines also indicate the wide range of excitation and ionization which exists in the atmosphere of ζ Pup. As an example, Table I shows that lines of N III (980 Å), N IV (1079 Å), and N V (1048–50 Å) originate at levels of 12.5, 53.0, and 76.3 volts respectively. These observations are completely consistent with those of similar type stars made in the visible spectral region.

None of the existing ultraviolet spectra of ζ Pup including the one presented here shows evidence for narrow, unshifted emission lines similar to the lines of He II (4686 Å), N III (4634–42 Å), and C III (5696 Å) characteristic of Of stars. A probable explanation is that no selective excitation such as the familiar fluorescence mechanisms which require large fluxes of He II (Lyman α) and H I (Lyman α) quanta are operating at wavelengths less than 1965 Å. As one might expect, however, it is very difficult to locate suitably a continuum flux level. It would be, therefore, impossible to detect any weak emission in the present data with reasonable certainty.

As has been pointed out it is likely that the P Cygni profile produced in N IV ions near 955 Å arises near the photosphere where dilution effects are weak. These ions exhibit a relatively small mean radial velocity (530 km sec^{-1}). On the other hand, the data of this experiment and that of Morton *et al.* reveal a P Cygni profile associated with a transition from a metastable triplet state in C III at 1175.7 Å. The mean radial velocity of the C III ions in this case is about 1700 km sec^{-1}. Further, it is known that such a situation can prevail only when the radiation is dilute, that is, when the C III ions are at distances of the order of several stellar radii from the center of the star. They would be further from the photosphere than the N IV ions which produced the 955 Å profile. Another point is that for any plausible atmospheric temperatures and pressures there should be no appreciable abundance of O VI, and yet the data indicate a large abundance of this ion in the circumstellar envelope. It is reasonable to assume that O VI ions with a mean radial velocity of 1900 km sec^{-1} are created well beyond the photosphere where suitable conditions exist. These data are therefore interpreted as evidence for a positive velocity gradient in the detectable part of the circumstellar envelope.

The degree of ionization appears to increase with increasing distance from the photosphere, but the lower levels of ionization as evidenced by the strong N III P Cygni profile at 991 Å are not completely depleted. The existence of a strong P Cygni profile at 1240 Å produced by N V ions is well established, and it is reasonable to expect that N IV exists in the ground state at roughly the same distances and velocities as N III and N V. We do not detect it because the resonance transitions lie at wavelengths less than 912 Å which are hidden from view by interstellar atomic hydrogen.

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Discussion

Burton: Do you observe the ^1S–^3P intersystem line of O v at 1218 Å? This line is similar to the 1909 Å C III line which has been observed with high intensity in the spectrum of γ Vel by Stecher. Since O IV and O VI lines are seen in your spectrum of ζ Pup, it is possible that [O v] 1218 Å will also be observed.

Smith: No, there seems to be no indication of this transition. Lyman α absorption due to interstellar atomic hydrogen predominates at this wavelength, and perhaps there is also a contribution to the observed absorption due to water vapor evaporating from the rocket and payload surfaces.

Morton: What is the basis for your wavelength scale and how accurately do you know your wavelengths?

Smith: I used the interstellar lines of Si II (1304.4 Å) and N I (1134.6) in addition to the telluric bands of N_2 (960.2–5.6 Å) to establish the scale. I believe the scale to be accurate to 0.3 Å.

Burton: (1) What type of photographic film was used for your observations? (2) What was the width of your spectrum (perpendicular to the direction of dispersion)?

Smith: In the case of the first question the answer is Kodak Pathé SC5. The width of the recorded spectrum is between 0.10 and 0.13 mm.