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The ultraviolet spectrum of ζ Tauri

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This report describes a study of the ultraviolet spectrum of the B-shell star, ζ Tauri. The observational material consists of high-dispersion spectrograms obtained from a rocket experiment launched in November 1972. The spectra cover the wavelength interval, 1100–2050 Å, with a resolution of about 0.1 Å. The u.v. stellar lines indicate that (1) the star has an effective temperature as high as 27000 K, (2) the stellar atmosphere appears to have serious abundance deficiencies in carbon and silicon, (3) the velocity field in the atmosphere is complicated but shows evidence for outward acceleration and differential rotation.

1. Introduction

Some of the problems that have arisen in the interpretation of B-emission stars are, first, what are the atmospheric properties of the stars? These properties are needed in order to understand a Be star's structure and evolutionary status and also to estimate its radiation field which interacts with the material in the envelope surrounding it. For many Be stars, the atmospheric parameters have proved difficult to estimate from analysis of visual line spectra because shell lines obscure all or portions of these lines. A second problem of interest has been, what is the mode of mass ejection from the star to the shell? For a long time, mass loss from Be stars has been considered a conceptually simple mechanism, namely rotational ejection. However, in the last decade, this simple model has been challenged (Slettebak 1966) because it was not possible to prove conclusively that any Be star was actually rotating at breakup velocity.

This report describes how the ultraviolet spectrum of one Be star, ζ Tauri, has proved useful in approaching these problems. The report is divided into three parts: first, a short description of the ultraviolet spectrum of ζ Tauri; next, a description of the results of an analysis of the ultraviolet stellar lines; and finally, a comparison of these results with those obtained from analyses of visual lines.

2. Observational material

The observational material consists of high dispersion u.v. spectrograms of ζ Tauri obtained from a rocket experiment in November 1972. Table 1 gives some of the relevant characteristics of the experiment and its performance. In addition, there are high-dispersion (2.2 Å/mm) visual spectrograms for comparison purposes. The visual spectrograms were obtained by Helmut Abt at the coudé focus of the 214 cm (84 inch) telescope of the Kitt Peak National Observatory on the night before the rocket launch.

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TABLE 1. ROCKET OBSERVATIONS

date	8 November 1972
wavelength coverage	1100–2050 Å
spectral resolution	0.1 Å
photographic density at continuum level	about 1.3
minimum rocket altitude during exposure	132 km
zenith distance of star during exposure	14°

3. The ultraviolet spectrum of ζ Tauri

Unlike the visual spectrum, there are no emission lines in the ultraviolet region of the spectrum. However, ζ Tauri does have an exceedingly rich absorption-line spectrum. Most of these lines probably arise in the shell. Figure 1 shows a graph of the line-blocking factors in the u.v. spectrum of ζ Tauri from 1410 to 2050 Å. We estimated these factors by first normalizing the high-resolution spectral tracings and then taking averages every 10 Å. The figure shows that the apparent continuum is depressed by about 0.25 *m* in the spectral range from 1500 to 2800 Å, and by up to 0.55 *m* in the region from 1800 to 2050 Å.

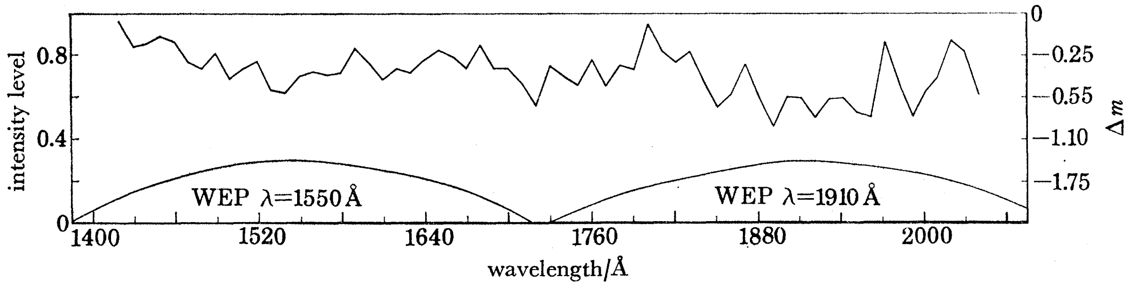

FIGURE 1. Rocket spectrum averaged over 10 Å intervals. The left-hand ordinate gives the intensity level normalized to 1.0 at the continuum, while the right-hand ordinate gives the apparent depression of the continuum in magnitudes. For comparison, the spectral sensitivity of the $\lambda = 1550$ Å and $\lambda = 1910$ Å filters on the Wisconsin experiment on board OAO-2 is shown below in a schematic fashion only.

This graph also serves as a simulated coarse-resolution scan of ζ Tauri, such as those obtained by the Wisconsin experiment (Code *et al.* 1970) on OAO-2 or by the S2 experiment (Boksenberg *et al.* 1973)on TD1. It shows the broad feature centred on 1920 Å that was first noted by Thompson, Humphries & Nandy (1974) in S2 spectra of B supergiants. It also shows the 1720 Å feature first noted by Underhill, Leckrone & West (1972) in OAO-2 spectra of B supergiants. Of course, ζ Tauri is not a supergiant. It is a main-sequence star, or nearly so, having a MK spectral type B3 IV. The appearance of these absorption features in this Be star and in supergiants suggests that these features are indicators of an extended atmosphere – both the shell of a Be star and the envelope of a supergiant.

Fortunately, we can go back to our original high-resolution tracings to see what these features consist of. Figure 2 shows a portion of the 1920 Å feature. The bottom section of the figure shows the actual spectrum of ζ Tauri, while the top part shows the wavelengths and intensities of the Fe III lines as listed by Kelly & Palumbo (1973). As Thompson *et al.* surmised, the 1920 Å feature appears to be largely due to Fe III, since the only high points in the rocket

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spectrum at 1864, 1935 and 1970–74 Å are precisely those places where there are no Fe III lines. The 1720 Å feature also appears to be composed largely of Fe II, Fe III, Ni III, and Al II shell lines.

4. Properties of the stellar u.v. spectrum

Happily, the spectrum below about 1500 Å is not so heavily blanketed by shell lines, and this region of the spectrum contains several stellar resonance lines. One of the main advantages, in fact, of the ultraviolet is that it contains strong resonance lines of abundant elements in high ionization states. These lines are useful in determining the atmospheric properties of the star because, being strong lines they are easily and accurately measured, and being in high ionization states they are not contaminated by shell components, and being resonance lines of abundant elements their associated atomic data are relatively reliable. The carbon and silicon lines have an added advantage that two ionization states are represented, so it is possible to use them for ionization-balance tests.

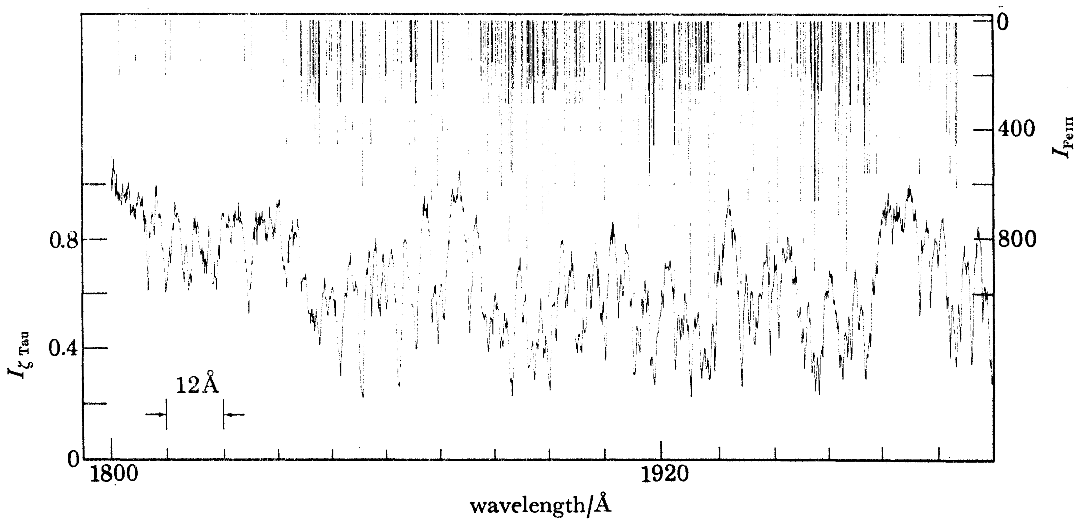

Figure 2. A portion of the rocket spectrum showing the λ = 1920 Å feature at high-dispersion. The left-hand ordinate gives the normalized intensity of the spectrum. The upper portion of the figure shows the intensity and wavelength of the Fe III lines listed by Kelly & Palumbo (1974), and the right-hand ordinate gives a measure of the intensities of these lines.

We have used our Laboratory's line-profile program to compute the l.t.e. strengths and profiles of the Si III, Si IV and the C III, C IV resonance lines and have compared them with the observed profiles in the spectrum of ζ Tauri. For these computations, Mihalas's (1972*a*) grid of models were used. Most of the atomic data (*f* values and natural damping constants) were taken from Morton & Hayden-Smith's (1973) compilation. The one exception was for the C III λ = 1175 Å line, where the data come from Weise, Smith & Glennon's (1966) work. The electron damping constants, which turn out to be very critical for these lines, were adopted from Sahal-Brèchot & Segre's (1971) values. Table 2 gives the actual atomic data used. A comparison of the theoretical profiles and the observed profiles of the carbon and silicon resonance lines yield several surprising results.

First, the observed ionization balance of Si III against Si IV and C III against C IV is best matched by Mihalas's model with the parameters, T_{eff} = 27 500 K and lg g = 4.0. The line

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TABLE 2. ATOMIC DATA

carbon

abundance

normal: C/total = 3.39×10^{-4}
low: C/total = 0.68×10^{-4} ($\frac{1}{5}$ normal)

ion	λ/Å	χ/cm^{-1}	lg gf	lg (γ_{nat}/s^{-1})	$\frac{\gamma_e}{N_e} \Big/ 10^{-6}$ s^{-1}
C III	1174.92	52390	−0.49	9.10	0.66
	1175.25	52367	−0.58	9.10	0.66
	1175.57	52390	−0.71	9.10	0.66
	1175.70	52447	−0.01	9.10	0.66
	1175.97	52390	−0.58	9.10	0.66
	1176.35	52447	−0.49	9.10	0.66
C IV	1548.20	0	−0.418	8.42	0.45
	1550.77	0	−0.720	8.42	0.45

silicon

abundance

normal: Si/total = 2.63×10^{-5}
low: Si/total = 0.526×10^{-5} ($\frac{1}{5}$ normal)

ion	λ/Å	χ/cm^{-1}	lg gf	lg (γ/s^{-1})	$\frac{\gamma_e}{N_e} \Big/ 10^{-6}$ s^{-1}
Si III	1206.51	0	+0.221	9.41	0.95
	1206.55	82884	+0.728	9.87	0.0
Si IV	1393.76	0	+0.023	8.96	0.90
	1402.77	0	−0.280	8.95	0.90

profiles computed from this model are illustrated in figure 3. The dashed lines and the dash-dot-dash lines show the theoretical profiles for a normal and $\frac{1}{5}$ normal abundance, respectively. The solid lines show the observed profiles. This figure shows that the observed carbon lines are somewhat weaker than even the lines computed for under-abundant carbon, and the observed silicon lines are significantly weaker than the computed lines for under-abundant silicon. At this stage, the degree of under-abundance is strongly dependent on the assumed electron damping constant. In view of the uncertainties in these values, we prefer not to attempt a precise estimate of the carbon and silicon abundances in the photosphere of ζ Tauri, but rather simply to show here the evidence for this surprisingly strong abundance anomaly.

The second surprising result of this study of the ultraviolet stellar lines was that the stellar lines are all shifted to shorter wavelengths. Now, the wavelength scale of the rocket spectrum was originally obtained on the assumption that the sharp shell lines are at their laboratory wavelengths. Actually, we know from Abt's visual spectrograms that the shell lines in November 1972 were redshifted by about 20 km/s with respect to the visual stellar lines, so we should expect that the ultraviolet stellar lines would appear shifted to shorter wavelengths by 20 km/s, or about 0.1 Å. In most cases, the stellar lines are blueshifted by more than this amount. The exact amount is shown under the word, 'shift', in figure 3. The shifts correspond to outward velocities of up to 120 km/s.

The third surprising feature of the ultraviolet stellar spectrum is the relative sharpness of the stellar lines. The computed lines profiles in figure 3 were all artificially rotated to correspond to a value of $v \sin i$ = 100 km/s, and they are comparable to the observed line widths. In the

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case of the C IV doublet, theoretical profiles where $v \sin i = 200$ km/s tend to blend, so we know the rotational velocity cannot be that high. In the case of the other lines, we find that the rotational velocity cannot be as high as 200 km/s or the central depths of the lines would be much smaller than observed.

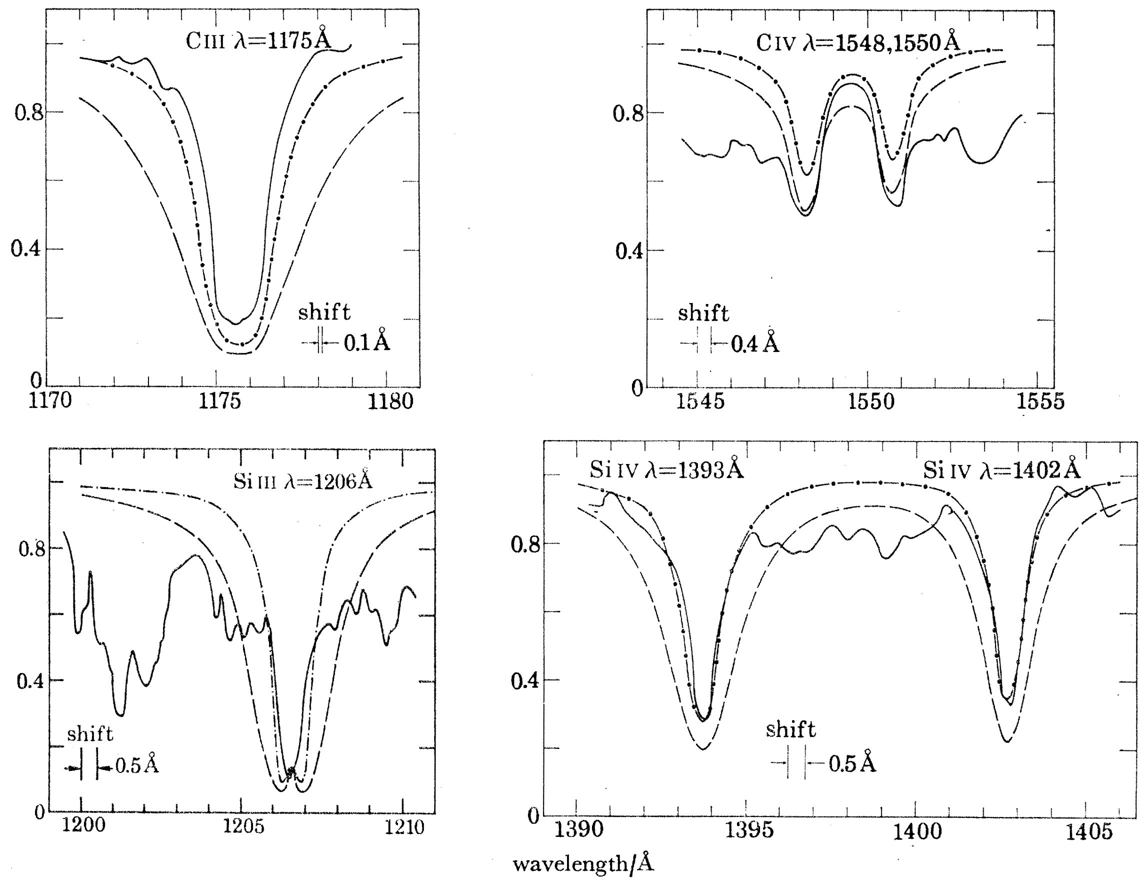

FIGURE 3. Comparison of observed and computed photospheric lines. The coding is as follows: ——, observed profile; – –, computed profile for normal abundance; - · –, computed profile for a fivefold under-abundance. The wavelength shift needed to centre the observed profiles on to the computed profiles is shown below in each figure.

5. Comparison with the visual spectrum

We should put these properties of ζ Tauri in context by comparing them with the visual properties of the star. First, we have seen that the u.v. resonance lines imply a temperature of about 27000 K, a value typical of B1 stars. No published quantitative analysis of the star's visual properties has been made, but the MK spectral type of the star is only B3 IV, which corresponds to an effective temperature of 20000 K or less (Mihalas 1972*b*). Secondly, the radial velocity of the u.v. stellar lines with respect to the shell lines is about 100 km/s, while the radial velocity of the visual stellar lines (i.e. the wings of the Balmer lines) with respect to the shell lines on Abt's plates is only about 20 km/s. Thirdly, the rotational velocity of the star implied by the u.v. lines must be definitely less than 200 km/s, while the rotational velocity of the star estimated by Slettebak (1949) and Underhill (1952) from the widths of visual stellar lines is 310 and 390 km/s respectively.

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We should keep in mind that in comparing the u.v. and visual properties we are, in fact, comparing the physical properties of different layers of the atmosphere. The u.v. lines which we have chosen to work with are very strong lines, so they are good indicators of the physical conditions in the outermost layers of the atmosphere, perhaps even the interface between the star and the shell. The visual lines, on the other hand, are generally weak lines, so they are good indicators of the properties of the deeper layers of the atmosphere. The implications of these discrepancies then – if we were to take them at their face value – are that there must be some sort of temperature inversion in order that a B3 star can have such strong C IV and Si IV lines. In addition, there must be an outward acceleration of atmospheric material in order to account for the large blueshifts of the strong u.v. lines. Finally, the star must be rotating differentially in order to account for the sharpness of the strong u.v. lines.

These implications are important to warrant further investigation. Are there any ways to reconcile the visual spectral properties of ζ Tauri to its u.v. spectral properties? We have tried to answer this question by comparing the observed visual line profiles from Abt's spectrograms with those computed by Mihalas (1972*a*) and Stoekley & Mihalas (1973). This comparison shows that yes, the visual line spectrum is probably compatible with an effective temperature of 27000 K. The wings of the hydrogen lines are so weak, in fact, that they imply an effective temperature somewhat greater than 27000 K on Mihalas's (1972*b*) temperature scale. The observed helium lines might also be compatible with an effective temperature as high as 27000 K, but only if one assumes a high rotational velocity (300 km/s) to account for strong, broad wings, and only if one assumes as well the existence of a significant He I shell component to account for the strong cores of the lines. In brief, the problem appears indeterminant: there simply is no way to pin down the effective temperature of ζ Tauri by means of the visual line spectrum, so it is a happy occasion to have access to a u.v. spectrum of the star.

The visual line spectrum also yields high conflicting values for the rotational velocity of the deeper atmospheric layers of ζ Tauri. If we simply measure the extent of the red wing of the Mg II λ = 4481 Å line, then we obtain a value for $v \sin i$ = 350 km/s, similar to the value which Underhill (1952) obtained by the same method. If we compare the observed profile of the He I λ = 4026 line with those computed by Stoekley & Mihalas (1973) from Mihalas's model atmospheres, we find that the broad wings of the line can be fit only on the assumption that $v \sin i$ = 300 km/s, a value in agreement with that of Slettebak. Hence, we come to conclude that the difference between the rotational velocities implied by the u.v. and visual lines is probably real, so that differential rotation is a distinct although not unsurprising possibility.

In addition, the difference in the radial velocities of the u.v. and visual stellar lines is undoubtedly real, so we conclude that there is good evidence for the acceleration of atmospheric material.

6. Conclusion

In conclusion, we have found from a study of the ultraviolet spectrum of ζ Tauri that the star is much hotter than originally supposed and that its atmosphere has a severe deficiency in silicon and a somewhat less severe deficiency in carbon. Secondly, we have found an apparent outward acceleration of atmospheric material. This radial velocity component, which is probably due to radiation pressure, certainly should be considered in attempting a model to explain mass-loss from this star. Finally, we have found preliminary evidence for differential rotation in the atmosphere of ζ Tauri, in the sense that the apparent rotational velocity decreases with increasing height above the photosphere.

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Because these conclusions are based on the study of only one Be star and because they have important implications, we suggest that spectral tracings of B stars from Copernicus be examined in a similar manner in order to find whether these conclusions hold true for all B stars, or for just Be stars, or for just ζ Tauri itself.

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