THE ASTROPHYSICAL JOURNAL, 217:90–94, 1977 October 1

HIGH-RESOLUTION ROCKET SPECTRA OF THE λ1920 AND λ1720 FEATURES IN THE SPECTRUM OF ZETA TAURI

SARA R. HEAP
NASA/Goddard Space Flight Center
Received 1976 December 2; revised 1977 February 7

ABSTRACT

High-resolution ultraviolet spectrograms of the B-shell star ζ Tau reveal two features characteristic of B supergiants, one at 1720 Å and the other at 1920 Å. The presence of these features in the spectrum of this object shows that they are indicative of an extended atmosphere—either the tenuous atmosphere of a supergiant or the envelope surrounding a rapidly rotating main-sequence star—and are therefore not purely luminosity criteria. The high spectral resolution allows an identification of the contributors to these features. The dominant contributor to the λ1920 feature is Fe^{++}, while the primary contributor to the λ1720 feature is Al^{+}.

Subject headings: line identification — stars: Be — stars: circumstellar shells — stars: individual — ultraviolet: spectra

I. INTRODUCTION

In the past decade, rocket and satellite experiments have obtained low-resolution ultraviolet spectra of numerous early-type stars, and preliminary spectral classification schemes based on gross ultraviolet spectral features have been worked out. Two useful features in this work have been absorption features near 1720 Å and 1920 Å. This paper reports on high-resolution spectra of ζ Tau, a B-shell star, which show both features. The following sections describe the experiment, observational data, identifications, and attempts at quantitative predictions.

II. THE OBSERVATIONS

Spectrograms of ζ Tau from 1100 to 2050 Å were obtained with spectrographs flown on an Aerobee 170 rocket launched from White Sands National Range on 1972 November 8. Two 1 m focal length spherical gratings, mounted as Wadsworth spectrographs, served to gather the incident starlight, and then to disperse and focus it onto a slightly curved surface. The spectra were recorded on Kodak 101-01 type film and had a nearly linear dispersion of 5.6 Å mm^{-1}. Because of the outstanding performance of the fine-guidance system, the spectral resolution was limited only by the focal properties of the grating and by the grain size of the film, and it is estimated to be 0.1 Å. The spectrograms were digitized on a Joyce-Loebl microdensitometer. Intensity calibration of the film was accomplished with the use of an HD curve derived from a vacuum–UV spot sensitometer developed by Dr. A. Smith in the Laboratory for Optical Astronomy, Goddard Space Flight Center. The wavelength scale was determined by a least-squares cubic fit of the microdensitometer sample numbers to the vacuum laboratory wavelengths of about 15 apparently unblended lines.

III. THE λ1920 FEATURE

After examining low-resolution UV spectral scans of early B stars that were obtained with the S2/68 experiment on TD1, Swings, Jamar, and Vreux (1973) reported the discovery of a broad absorption feature nearly symmetrical centered at about 1920 Å, which they tentatively identified as due to a confluence of Fe III lines. Thompson, Humphries, and Nandy (1974) then found that the strength of the feature is related to stellar luminosity: in main-sequence stars, the λ1920 feature is present but very shallow, while in early B supergiants such as o^2 CMa, the feature is up to 0.3 mag deep. Swings, Klutz, and Vreux (1976) have developed these points in a recent paper.

Our rocket spectra of the shell star ζ Tau also show the λ1920 feature, and it has a strength even greater than that in B supergiants. The appearance of the λ1920 feature in the spectrum of ζ Tau shows that the feature is indicative of an extended atmosphere—either the tenuous atmosphere of a supergiant or the envelope surrounding a rapidly rotating main-sequence star—and is therefore not purely a luminosity criterion. Furthermore, the high-dispersion spectra of ζ Tau resolve the lines which form the λ1920 feature, and they show that, as in the supergiant spectra, the majority of them are due to Fe III. Figure 1 compares a segment of the original spectrograms, 1800–2040 Å, of ζ Tau with the laboratory spectrum of Fe III in the region 1800–1980 Å. The wavelengths and relative intensities of the Fe III lines are those given by Kelly and Palumbo (1973), based mainly on laboratory studies by Edlén and Swings (1942). A strong correlation between the strength of an observed absorption feature and the laboratory intensities of the Fe III lines is evident. Note, for example, that the only high points in the rocket spectrum (at 1864, 1935, and 1970–1974 Å) are precisely those regions

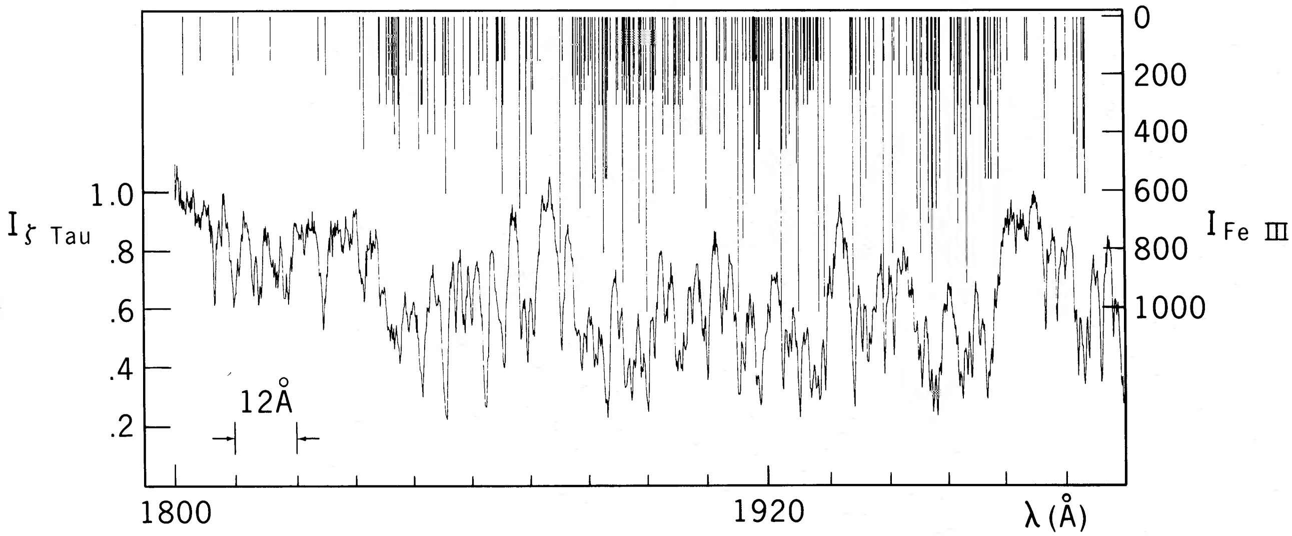

FIG. 1.—A segment of the rocket spectrum of ζ Tau showing the λ1920 feature at high resolution. The left-hand ordinate gives the normalized flux. The upper portion of the figure shows the relative intensities and wavelengths of Fe III lines, as listed by Kelly and Palumbo (1973). The right-hand ordinate gives a measure of the intensities of these lines.

where there are no Fe III lines. We therefore conclude that the λ1920 feature in the spectrum of ζ Tau is due to absorption by Fe^{++}. The Fe^{++} ions are most probably formed in the shell, since the observed lines have the characteristic sharpness of shell lines and since the physical conditions in the shell ($N_e \approx 10^{11}$ cm^{-3}, $T_e \approx$ 10,000 K) are suitable for a maximum Fe^{++} population.

IV. THE λ1720 FEATURE

Underhill, Leckrone, and West (1972) used the Wisconsin experiment on OAO-2 to scan B-type stars over the spectral interval 1170–1770 Å, with approximately 10 Å resolution. They found an absorption feature at about 1720 Å that was correlated with the presence of an extended atmosphere: in B main-sequence stars, the feature was absent, while in B supergiants and in the B-shell star ζ Tau the absorption feature became quite prominent. Underhill *et al.* suggested that the feature is a fortuitous blend of atomic lines that becomes strengthened in extended atmospheres, while Tarafdar and Vardya (1973) suggested that the feature is due to the A–X band of CO and/or the B–X band of H_2, two molecules which they thought might possibly survive in an extended atmosphere.

The rocket spectrum of ζ Tau reproduced in Figure 2 shows the λ1720 feature with a strength about that found by Underhill *et al.* The Al II multiplet at λλ1719.5, 1721.3, and 1725.0 is especially prominent and immediately identifiable. The observed strength of this multiplet is not surprising, since the resonance transition of Al II at 1670 Å is a very strong shell line which has an equivalent width W_λ = 1.1 Å, and since the Al II multiplet at $\lambda \approx$ 1720 Å arises from a metastable level only 4.6 eV above the ground state. It is possible that this multiplet is strengthened by the "dilution effect" over its LTE strength. Other features in the spectrum of ζ Tau near 1720 Å, such as those at λλ1715.5, 1722.7, and 1730.0, are not identified as any one atomic line. However, atomic line lists (Kelly and Palumbo 1973) and atomic data (Kurucz and Peytremann 1974) indicate numerous "strong" lines of Fe II, Fe III, Ni II, and Ni III in the vicinity of 1720 Å. Lines of these spectra are definitely present in other spectral regions, so it is probable that these lines blend with one another to produce the observed feature at λ1720.

We therefore conclude that much (if not all) of the λ1720 feature is due to absorption by Al II, Fe II, and Fe III, and Ni II and Ni III. The ions Al^+, Fe^+, and Ni^+ could not possibly survive in the atmosphere of such a hot star as ζ Tau, which has the parameters, T_{eff} = 27,500 K, log g = 4.0 (Heap 1975), and so they must be formed in the shell where the physical conditions ($T_e \approx$ 10,000 K, $N_e = 10^{11}$ cm^{-3}) are suitable for their presence.

A possible molecular origin for the λ1720 feature suggested by Tarafdar and Vardya was not ruled out, but it appears to be unlikely. D. York (1974) has found no evidence of shell H_2 in *Copernicus* spectra of ζ Tau below 1200 Å, so we have excluded this molecule from further study. Carbon monoxide is also an improbable source of shell opacity, since C I, whose ionization potential is about the same as the dissociation energy of CO, is not found in the spectrum of ζ Tau. Nevertheless, we made a search for evidence of absorption from the lowest vibrational levels of the $X\,^1\Sigma^+$ state of CO. The results are not definitive, because the identification of CO features was complicated by uncertainty in the expected widths and wavelengths of the various vibrational electronic transitions, and by obscuration by numerous, strong atomic lines

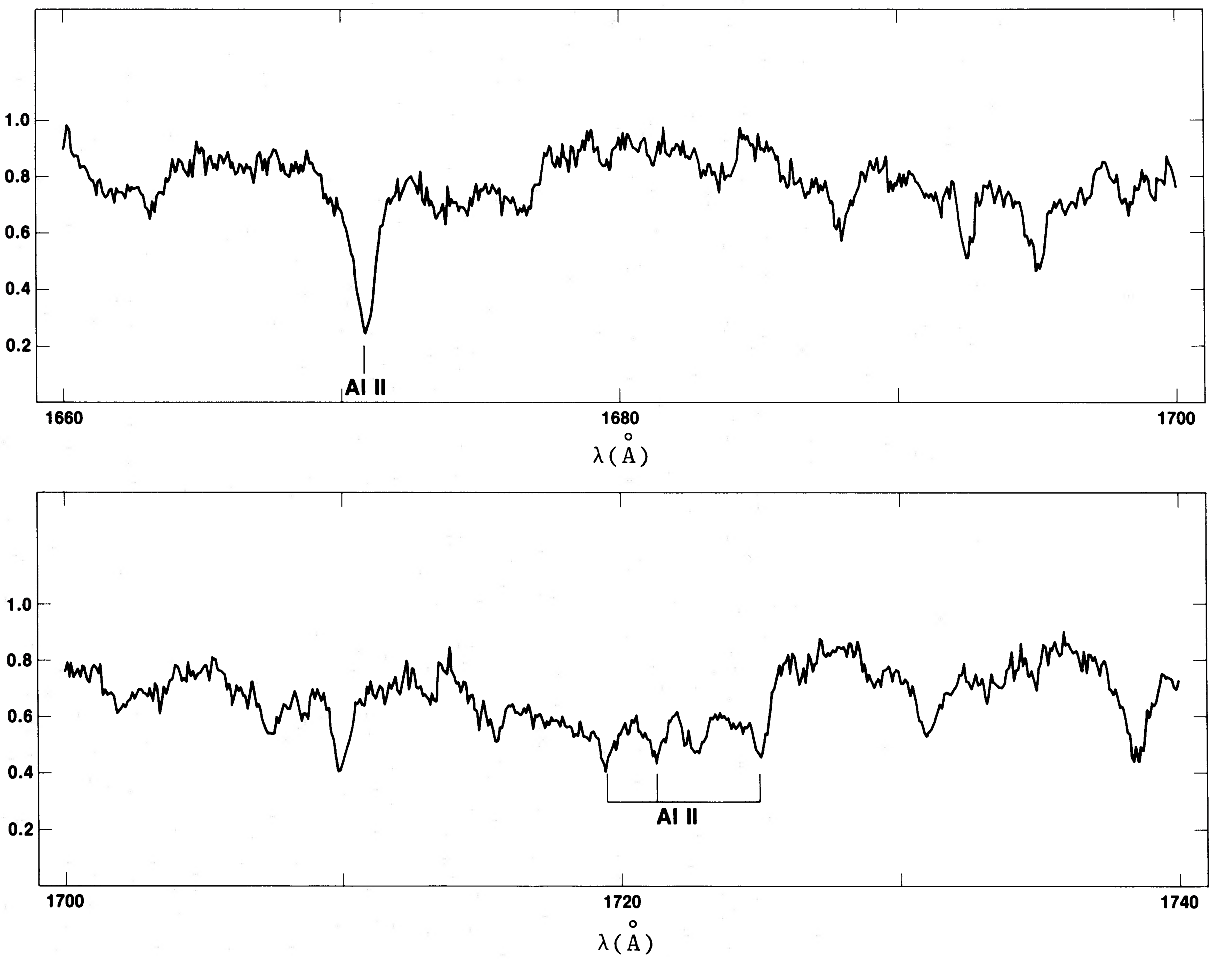

FIG. 2.—A segment of the rocket spectrum of ζ Tau showing the λ1720 feature at high resolution

in the spectrum of ζ Tau. Even so, it appears that CO could not be the principal contributor to the λ1720 feature, for the following reason. The strongest band of CO near 1720 Å is due to the $v'' = 0$ to $v' = 3$ transition (see Goldberg, Parkinson, and Reeve 1965). If this band were a principal source of opacity in the shell of ζ Tau, then other strong CO bands should also be present. Table 1 lists the wavelengths of some transitions which are expected to be strong. These wavelengths were calculated according to formulae given by Krupenie (1966), and an assumed electron temperature of 10,000 K, appropriate to the shell of ζ Tau. Under such conditions, the maximum population of the lowest vibrational levels of the $X\,^1\Sigma^+$ state occurs at the rotational levels, $J = 42$ or 43. Table 1 lists the wavelengths of selected $A^1\Pi$–$X\,^1\Sigma^+$ transitions from the J_{max} level for $\Delta J = 0, \pm 1$. We have used this table as a finding list for CO in the spectrum of ζ Tau without success, so we conclude that CO cannot be the principal contributor to the λ1720 absorption feature.

TABLE 1

FINDING LIST FOR CO IN SHELL OF ζ TAURI

Transition			λ		
v''	v'	$J_{max}(v'')$	$\Delta J = -1$	$\Delta J = 0$	$\Delta J = +1$
0.........	0	42	1561.7	1558.4	1555.1
1.........	0	42	1615.0	1611.5	1607.1
2.........	0	42	1671.2	1667.5	1663.7
3.........	1	43	1689.4	1685.6	1681.6
3.........	0	43	1731.6	1727.5	1723.3
4.........	1	43	1749.4	1745.3	1741.1

V. CALCULATION OF THE SPECTRAL REGION NEAR 1720 Å

Since, with the exception of Al II, the lines which form the λ1720 feature are blended and thus not conclusively identified, we have computed synthetic spectra in the region λλ1710–1740, in order (1) to check whether Fe^+, Fe^{++}, Ni^+, and Ni^{++} are substantial sources of opacity in the atmospheres of B stars; and (2) to check whether the λ1720 feature does not appear at lower surface gravities. We found from these calculations that Fe and Ni are indeed the main contributors in line blocking in the spectra of early and middle B stars in the spectral region λλ1710–1740, but that the line strengths of these elements did not change with decreasing gravity in such a way that the λ1720 feature would appear. Below, we describe in more detail the computations and results.

We have used Mihalas's (1972) model atmospheres and Kurucz and Peytremann's (1974) semiempirical *gf*-values to calculate fluxes in the spectral region near 1720 Å. Two model atmospheres from Mihalas's (1972) grid were chosen. One model has the parameters, $T_{\text{eff}} = 27{,}500$ K, $\log g = 4.0$, and is believed to represent the atmospheres of early B main-sequence stars, while the other model has the parameters, $T_{\text{eff}} = 27{,}500$ K, $\log g = 3.0$, and should represent the atmospheres of early B supergiants. The composition of the atmosphere was assumed to include the elements, H, He, C, N, O, Mg, Al, Si, P, S, Ti, Cr, Fe, and Ni, with normal abundances. The calculations assumed line formation in LTE and line profiles given by the Voigt function with a classical damping constant and 5 km s^{-1} microturbulent velocity. The wavelength spacing was set in such a way that the flux was always computed at each line center and a distance ± 0.02 Å off of line center, as well as in between the lines. The computed spectra of the interval 1710–1740 Å contained nearly 500 wavelength points.

The synthetic spectra produced from these two models show about 100 distant absorption lines in the spectral region 1710–1740 Å, nearly all of which are due to Fe^{++} and Ni^{++}. In order to show the magnitude of line blocking produced by these two ions and also to simulate the properties of ζ Tau, the computed fluxes were artificially rotated to correspond to a projected equatorial velocity of 200 km s^{-1}. The rotated spectra are compared with the spectrum of ζ Tau in Figure 3. It is important to note that not one feature or ripple in the computed spectra is associated with a given line. The presence of a feature or ripple is due to the way in which many lines blend together. Two problematic conclusions can be drawn from an examination of this figure. The first is that the calculated degree of line blocking is sometimes greater than that observed in ζ Tau. We had expected that the computed spectrum of the $T_{\text{eff}} = 27{,}500$ K, $\log g = 4$ model would adequately represent the observed absorption spectrum of the photosphere of ζ Tau and thus provide a baseline against which to distinguish the shell contribution to the observed absorption spectrum. This has not turned out to be the case: in some intervals (i.e., 1726–1730, 1731–1735 Å), the computed photospheric absorption is even stronger than the observed (photospheric plus shell) absorption. The second conclusion is that the calculated trend of line blocking with gravity in this spectral region is contrary to the observed trend. Underhill *et al.*'s observations show the appearance of the λ1720 absorption feature in early B stars as one goes to lower gravities. The calculations show no appearance of such a feature: the total line blocking in the 1710–1740 spectral region actually decreased with decreasing gravity, and the degree of line blocking at about 1720 Å with respect to that at around 1710 and 1730 Å remained the same. An explanation for the general decrease in line blocking with lower gravity is the increased ionization of the main absorbers—Fe^{++} to Fe^{+++} and Ni^{++} to Ni^{+++}—due to the lower electron density in the line-forming regions of the atmosphere.

For comparison, similar computations were carried out for two other model atmospheres in the Mihalas grid, one having the parameters $T_{\text{eff}} = 15{,}000$ K, $\log g = 4.0$, and the other having the parameters $T_{\text{eff}} = 15{,}000$ K, $\log g = 2.5$. In these two models, the main absorbers in the 1710–1740 Å interval are Fe^{+}, Fe^{++}, Ni^{+}, and Ni^{++}, with approximately equal contributions. At $T_{\text{eff}} = 15{,}000$ K, the absorption in this spectral interval actually does increase at lower gravities, but in a uniform way, so that no feature near λ1720 appears.

VI. SUMMARY

The high-dispersion spectrograms of the shell star ζ Tau have provided a means of identifying two UV

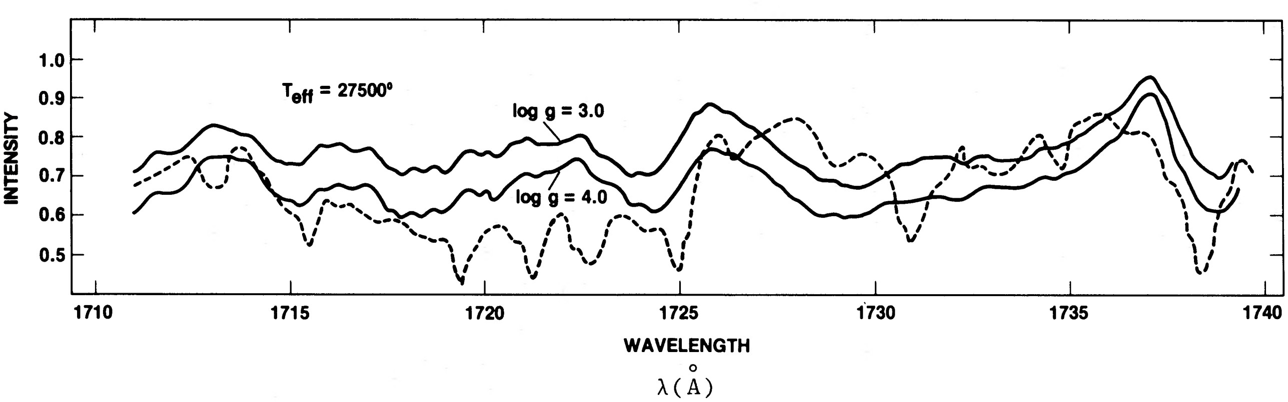

FIG. 3.—Calculated spectra and observed spectrum, including the λ1720 feature. The solid lines show the computed spectra artificially rotated to correspond to 200 km s^{-1}, while the dashed line shows the observed spectrum of ζ Tau.

absorption features, the λ1920 and λ1720 features, which are associated with the presence of an extended atmosphere or circumstellar shell. These spectrograms show that the λ1920 feature in ζ Tau is principally due to Fe III, and that the λ1720 feature in ζ Tau is definitely due to Al II and probably Fe II, Fe III, Ni II, and Ni III as well. It is probable that the same identifications apply to early B supergiants. However, quantitative predictions do not produce the observed luminosity dependence of the λ1720 feature.

REFERENCES

Boksenberg, A., Evans, R. G., Fowler, R. G., Gardner, I. S. K., Houziaux, L., Humphries, C. M., Jamar, C., Macau, D., Macau, J. P., Malaise, D., Monfils, A., Nandy, J., Thompson, G. I., Wilson, R., and Wroe, H. 1973, *M.N.R.A.S.*, **163**, 291.
Code, A. D. 1972, ed., *Scientific Results from the OAO-2* (NASA SP-310).
Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F. 1970, *Ap. J.*, **161**, 377.
Edlén, R., and Swings, P. 1942, *Ap. J.*, **95**, 532.
Goldberg, L., Parkinson, W. H., and Reeve, E. M. 1965, *Ap. J.*, **141**, 1293.
Heap, S. R. 1975, *Phil. Trans. Roy. Soc. London*, *A*, **279**, 371.
Herzberg, G. 1961, *Spectra of Diatomic Molecules* (Princeton: Van Nostrand).
Kamp, L. W. 1974, private communication.
Kelly, R. L., and Palumbo, L. 1973, *Atomic and Ionic Emission Lines below 2000 Angstroms* (NRL Report 7599).
Krupenie, P. H. 1966, *The Band Spectrum of Carbon Monoxide* (NSRDS-NBS5).
Kurucz, R., and Peytremann, E. 1974, preprint.
Mihalas, D. M. 1972, *Non-LTE Model Atmospheres for B and O Stars* (NCAR-TN/STR-76).
Swings, J. P., Jamar, G., and Vreux, J. M. 1973, *Astr. Ap.*, **29**, 207.
Swings, J. P., Klutz, M., and Vreux, J. M. 1976, *Astr. Ap. Suppl.*, **25**, 193.
Tarafdar, S. P., and Vardya, M. S. 1973, *M.N.R.A.S.*, **163**, 35.
Thompson, G. I., Humphries, C. M., and Nandy, K. 1974, *Ap. J. (Letters)*, **187**, L81.
Underhill, A. B., Leckrone, D. S., and West, D. K. 1972, *Ap. J.*, **171**, 63.
Withbroe, G. 1971, in *The Menzel Symposium*, ed. K. B. Gebbie (NBS Special Pub. 353), p. 127.
York, D. 1974, private communication.

S. R. HEAP: Code 672, Goddard Space Flight Center, Greenbelt, MD 20771