TURBULENCE IN THE ATMOSPHERES OF ECLIPSING BINARY STARS

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Abstract: A review of the orbits and dimensions of the ζ Aurigae systems is given, based on photometric and spectrographic observations. The Ca II K-line has been studied intensively to determine the extent and uneven structure of the chromospheres of these stars; the multiple structure of this line observed at several eclipses confirms the presence of large-scale clouds in the atmospheres. Measurements of line profiles and equivalent widths show that macroturbulent velocities up to 10 km/sec in the upper chromosphere, and up to 20 km/sec. in the lower chromosphere are present. Microturbulent velocities in the lower chromosphere are about 10 km/sec. Recent ultraviolet observations indicate that the B star in the 32 Cygni system may be within the outer chromosphere of the giant component and its radiation may affect the chromospheric structure more than had previously been suggested.

In the study of stellar atmospheres the composition and structure at increasing heights above the photosphere are required. The sun is the only star whose chromosphere can be observed directly. The other principal source for observing such structure is in the ζ Aurigae stars where, during ingress and egress at eclipse, the relatively small, hot, secondary component acts as a probe when its radiation passes through the atmosphere of the much-larger late-type primary star. Much information can be obtained from the light curves of these stars concerning the types of the components and their relative dimensions, while irregularities in the curves during ingress and egress phases may indicate disturbances in their atmospheres. However, it is important that both photometric and high-resolution spectrographic observations be combined in order to obtain the maximum knowledge about each system and the individual component stars. For many years I.A.U. Commission 42 on Close Binary Stars has stressed the need for such observations and a number of cooperative programs have been sucessfully carried out.

The spectrographic data can be used in a number of ways. The orbital elements of the system can be determined from the radial velocities when one or more cycles are covered. Although the lines in the secondary component are usually difficult to measure, radial velocities can be obtained and, knowing that the inclination must be near 90°, the masses can be determined. In some cases there is a circumstellar cloud surrounding the system and its structure can be inferred from changes in the spectra over the cycle. Close to eclipse major changes in the low-excitation lines of both neutral and ionized atoms can be seen. Detailed analysis of the intensities of these lines give numerical values for the temperature, pressure and composition of the outer atmospheres of the giant component of the system at various heights above the photosphere. The intensities and profiles of the lines in these spectra give indications of the turbulence and other mass motions in the atmosphere that we have come to discuss at this colloquium. It has usually been assumed that the atmospheres of these giant stars are similar to single stars since the components are not close, relative to most binary systems, as the periods are hundreds of days rather than a few days or less. However, there have been suggestions that the hot component does affect the structure of the giant companion, which is the principal object of many of our investigations.

Quite an extensive literature on the ζ Aurigae stars has been built up over the past forty years. We shall discuss only the principal systems, ζ Aurigae, 31 and 32 Cygni and VV Cephei since they are the brightest examples and therefore have been studied most intensively and with the highest spectrographic dispersion. The standard work on the detailed analysis of these systems was written by Wilson (1960). Wright (1970, 1973) up-dated the survey of the orbits and dimensions of the ζ Aurigae stars and reviewed the changes of the Ca II K-line that had been observed at several eclipses. Cowley (1969) surveyed the literature on the VV Cephei stars and noted that several of these stars, especially AZ Cassiopeiae, WY Geminorum and Boss 1985, may be eclipsing systems that would warrant more systematic study. Recently Sahade and Wood (1978) examined the close binary systems and included a section on atmospheric eclipses. Observational programs have been continued in recent years, especially by Hack and Faraggiana, by Kitamura and his associates and by Wright. New studies of these systems should become available in the relatively near future.

Since this colloquium has been organized to discuss turbulence in stellar atmospheres, this paper will be devoted to brief discussions of current data available for the four principal systems: their orbits and dimensions which are required to give the scale for determining the atmospheric structure; the observations of the Ca II K-line that can be observed higher in the atmosphere than most other lines; and the curve-of-growth analyses that determine the microturbulence as well as other atmospheric parameters.

TABLE 1. ORBITS AND DIMENSIONS OF THE ζ AURIGAE STARS

	ζ Aurigae		32 Cygni		31 Cygni		VV Cephei	
	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary
Period P days	972.160		1147.8		3784.3		7430.5	
Eccentricity e	0.41		0.30		0.22		0.35	
Longitude of Periastron ω°	336.0		218.2		201.1		59.2	
Periastron Passage, T JD 2,400,000+	34585.74		33141.80		37169.73		38461.0	
Mid-eclipse JD 2,400,000+	27692.82		40110.		37685.65		35931.	
Systemic Velocity V_0 km/sec.	+12.9		-5.7		-7.7	-12.3	-20.2	-18.5
Semi-amplitude K km/sec.	24.6	31.4	17.0	34.	14.0	20.8	19.4	19.1
Semi-major axis a sin i ($x10^8$)km.	3.00	3.83	2.56	5.12	7.11	10.6	18.6	18.3
Inclination,°	90		82		88		77	
Spectrum	K4 Ib	B6 V	K5 Ib	B6 V	K4 Ib	B4 V	M2ep Ia	08
Luminosity, Mv	-3.5	-1.3	-3.3	0.1	-4.6	-2.0	-7.5	-3
Temperature, T_{eff}°	3550	15,400	3315	15,400	3550	17,600	3000	25,000
Diameter Θ	200	5	250	2.0	210	5.5	1600	13
Mass, $M_{\odot}$ sin i	7.54	5.91	9.15	4.85	9.16	6.19	18.0	18.2

ORBITS AND DIMENSIONS

The orbits and dimensions of these eclipsing binary systems are not as well determined as might be desired, partly because the periods are long and few cycles have been covered, the light curves show some changes from eclipse to eclipse, and the secondary spectra are difficult to measure because the multi-lined K - or M - type spectrum dominates most of the wavelength range that is covered; data derived from light curves and spectrographic observations do not always agree. Nevertheless the results are sufficiently accurate to give an adequate scale of the atmosphere. The best available data are listed in Table 1. No more precise orbital data for ζ Aurigae, 31 and 32 Cygni have been published since Wright's (1970) review; those for VV Cephei are from Wright (1977) and are based on measurements of the Hα line for the O-type star and lines in the same region of the spectrum for the M-type star. Some revisions for the luminosities, masses and diameters have been considered: for ζ Aurigae, Kiyokawa and Kitamura (1973) revised the light-curve data for M_V, T_{eff} and the diameter of the K-type star; for 32 Cygni the Saijo and Saito (1977) analysis of the light curve indicated that the spectrum of the B-type star is probably B8 rather than B4 with corresponding revisions for the temperature and the diameters; they also suggested small changes in the masses. Koch et al. (1970) rank the photometric data for these systems in the category of "lowest reliability", chiefly because the light curves show some variability, and the eclipses are atmospheric and therefore the depth of eclipse varies with wavelength.

It is worth mentioning that, for ζ Aurigae, Kiyokawa (1967) discussed the light curves for five eclipses from 1935 to 1963-64 and found a small increase in the length of totality with time, which suggested a gradual expansion of the atmosphere of the primary star, but Kitamura (1974) found that narrow-band observations of the 1963-64 eclipse indicated a shorter time for total eclipse, which leaves the question of changes in the size of the K-type star still open.

It has been known for many years that the eclipse for 32 Cygni is grazing; the observations were discussed by Wright (1970). Wellmann (1957) decided that totality lasted for 9 days in 1949, and 12 days in 1952, while Scholz (1965) concluded that the eclipse was total for 6 days in 1962, and Herczeg and Schmidt (1963) considered that totality lasted between 1 and 3 days for the same eclipse. However, Saito and Sato (1972) analyzed the numerous observations made by the Japanese observers for the 1968 and 1971 eclipses and concluded that these eclipses were grazing and almost total, but showed no flat-bottomed minimum in the light curve that would indicate totality. Thus it appears probable that, for 32 Cygni, changes in the extent of the outer atmosphere do occur. It has been known, of course, that the opacity varies with wavelength and that the eclipses are much deeper in the ultraviolet region of the spectrum than in the red. Thus in the far ultraviolet region, the eclipses of 1968 and 1971 may have been effectively total. The Victoria spectrographic observations of Wright and Hesse (1969), based chiefly on the appearance of the K-line indicated that totality lasted 12 days in 1965 and 8 days in 1962.

RADIAL VELOCITY OBSERVATIONS OF THE CA II K-LINE

The K-line in the spectra of the ζ Aurigae stars has been studied intensively and many measures of radial velocity and intensity have been published. For ζ Aurigae the velocities of all lines, including the K-line, are more positive relative to the orbital velocity during the ingress phase and more negative at egress. However, the displacements, though in the same general direction as those that might be expected for a rotating star, are more random in character and do not fit the pattern predicted even for a slow rotation. Wilson (1960) concluded that the rotation effect must be small, that there is a chromospheric equatorial current and that the chromosphere contains sizeable concentrations of matter moving with different velocities. Saito (1970) studied the problem for ζ Aurigae and concluded that the hydrogen gas facing the B-type star should be ionized by the ultraviolet radiation of the hot star and an ionization front is formed as a boundary between the H I and H II regions. For ζ Aurigae Saito concluded that the velocity field of the K-type chromosphere consists of a non-steady field due to gas clouds moving with different velocities overlapping the main velocity field of gas expanding from the K star at an ejection rate of 1×10^{-8} $M_{\odot}$/year and a rotation rate of 5 km/sec. At some distance away from the K-type star in the direction of the B star velocities at egress are produced by the H I gas accelerated by Lyman quanta from the B star. Moderately good agreement between Saito's theoretical curve and the chromospheric observed radial velocities suggest that this proposed interpretation may have some validity. Velocities of chromospheric lines of other atoms, including Fe I and Ca II follow a pattern somewhat similar to the hydrogen lines.

On the other hand, observations of the Ca II K-line at the 1951 and 1961 eclipses of 31 Cygni (McKeller et al. 1959, Wright and Odgers, 1962) show that the radial velocities follow the orbital curve fairly closely with numerous negative displacements up to 20 km/sec during the ingress phases. In 1951 the K-line was clearly resolved into two components during the egress phases, with the mean velocity displaced above the orbital velocity curve; no observations could be made during the 1962 egress. The multiple structure of the K-line has been a feature of the chromospheric phases. This structure has been attributed to a small number of "clouds" possibly detached from the star in some cases where the displaced velocities are greater than the velocity of escape; the satellite line is usually sharper than the main component and can sometimes be observed for several days with nearly the same velocity. The velocities of the principal line during both ingress and egress seem to suggest a strong circulation in the K-star chromosphere moving in the opposite sense to the orbital motion and also in the opposite sense to that in ζ Aurigae.

For 32 Cygni the most extensive series of measurements are those of Wright and Hesse (1969) for the 1965 eclipse, and of Bisiacchi et al. (1974) for the 1971 eclipse. The trends of the radial velocities of the K-line are similar at each eclipse: There is considerable structure in the lines within about 40 days of mid-eclipse and the components can frequently be separated. The general trend is towards velocities slightly greater than the orbital velocity before mid-eclipse and slightly less after mid-eclipse. Bisiacchi et al. suggest that there may be some kind of cyclic oscillation in the atmosphere of the K-type star indicated by the measurements of the Fe I lines.

INTENSITY OBSERVATIONS OF THE CA II K-LINE

Wright's (1970) review of the intensity data for the chromospheric K-line observed in the ζ Aurigae stars still covers most of the data available. The K-line intensities can be measured two stellar diameters or more away from the photosphere (second contact) and the complex structure can often be seen at any phase as the radiation from the B-type star passes through the outer atmosphere of the K-type star.

Kawabata and Saito (1975) have published their data for the 1971-72 eclipse of ζ Aurigae. They obtained several plates on each of a number of nights during ingress and egress and found that the several satellite lines could nearly always be seen on each spectrogram obtained on a given night - thus confirming the reality of the components. The chromosphere of ζ Aurigae has now been observed for forty years. The K-line intensities may vary by as much as a factor of two from eclipse to eclipse; if they are weak during ingress they are also weak during egress. Thus the plots of the intensities at ingress and egress are quite similar, but are not necessarily mirror images. The intensities of the K-line at the eclipses of 1934, 1938 and 1971 are classified as weak. Those observed at Cambridge in 1937 are the strongest. The 1937 observations may be unusual, perhaps due to some kind of eruption at the time of the observations. The data for the 1947, 1950 and 1955-56 eclipses are listed as moderate. Kawabata and Saito suggest that the chromospheric activity of ζ Aurigae increased from 1939 until 1950-56, when it reached a maximum, and then decreased until 1971.

The K-line intensities in the spectrum of 31 Cygni for the eclipses of 1951 and 1961 have been studied by McKellar et al. (1959) and by Wright and Odgers (1962). The 1951 observations showed the component structure clearly, especially during the egress phases. The multiple structure was confirmed at the 1961 eclipse when numerous plates were obtained during ingress; a strong, negatively-displaced component was observed 5 stellar radii from the edge of the K-type star. The principal line increased in intensity from narrow to broad (1 Å) about one radius from the limb and then its width decreased for several days before it broadened again and showed the characteristic "square" appearance of a strong chromospheric line; the damping wings then began to appear as the probe passed through the innermost portions of the chromosphere. The decrease in breadth of the line so close to the limb seems to indicate that the density of the chromosphere is not uniform and, since the observations do not repeat at each eclipse, non-stable.

The chromospheric intensities for the 32 Cygni system for eclipses since 1949 have been discussed by Wright and Hesse (1969) and by Bisiacchi et al. (1975). The trends from eclipse to eclipse seem to be random. The intensities were least at the 1962 eclipse and greatest in 1965. At both the 1965 and 1971 eclipses the component structure is more evident during ingress than at egress, but the widths in 1965 were nearly fifty per cent greater than in 1971. However, these variations from one eclipse to another are not surprising in these cloudy, unstable atmospheres.

As the Ca II K-line shows the greatest changes during the eclipse phases, since it is the strongest line in the spectrum, its profile has been used to determine macroturbulent velocities. Perhaps the most careful determination of the profile has been made by Kitamura (1967) for ζ Aurigae. He made corrections for the effect of the B-type star on the observed continuum and for the K-line in the K-type spectrum. At a height of 16 x 10^6 km above the limb, Kitamura found a best fit between calculated and observed profile for a turbulent velocity of 15 - 19 km/sec. and a total number of 1 - 4 x 10^{16} Ca II atoms in the line of sight. The fit with the theoretical curve is good but not excellent, partly because the observed profile has a small still-stand near half-intensity; the observed intensity change is more gradual than the theoretical profile at both zero intensity and at the continuum.

For 31 Cygni, McKellar et al. (1959) studied Victoria spectra obtained at the 1951 eclipse in some detail. They compared observed and computed profiles for both the principal lines and the satellite lines observed during egress. For the narrow lines far out in the chromosphere they found reasonable agreement with the observations by assuming a turbulent velocity of 10 km/sec. and 10^{12} atoms per unit cross section in the line of sight. For the broad lines in the inner chromosphere the turbulent velocity was 20 km/sec. and 10^{18} atoms. Underhill (1954) measured the profiles of a number of Fe I lines near K-line on the 1951 Victoria chromospheric spectra and concluded that the turbulent velocity for these lines was similar to that of the K-line for the inner chromosphere. The intensities of the Fe I lines decrease much more rapidly than those of the K-line and no estimates could be made for the outer chromosphere.

CHROMOSPHERIC INTENSITIES OF METALLIC LINES

Spectrograms obtained during ingress and egress for the ζ Aurigae giant eclipsing systems contain a wealth of information that can be used to determine the parameters of the chromosphere. No detailed analyses have yet been published using model-atmosphere calculations chiefly because the outer atmosphere of these stars seems to be unstable. Since condensations (prominences, clouds, etc.) are observed for the ionized calcium atoms, similar features may affect the intensities of other atoms. Since the radiation of the B-type secondary spectrum is effectively the continuum of the chromospheric lines, though some chromospheric continuum may also be present and the presence of the K-type spectrum must also be taken into account, curve-of-growth methods using a Schuster-Schwarzschild model with exponential absorption (van der Held, 1931, Unsöld, 1955) have been adopted in most of the published investigations. The standard work on the analysis of chromospheric line intensities is still that of Wilson (1960) who discussed the data available up to 1959. Wright's (1959) analysis of the 1951 eclipse data for 31 Cygni was published just after Wilson's survey and agrees with Wilson's principal conclusions although slightly different methods of reduction were used.

In order to determine the chromospheric intensities, plates obtained well outside of eclipse showing the normal composite spectrum and also plates taken during totality are required. The effect of the K-type spectrum must be removed and the chromospheric equivalent widths relative to the B-type probe are determined as discussed by Wilson (1960) and by Wright (1959).

In the curve-of-growth analysis of the data, the ordinate of the plot is log (W/λ) for the observed quantities and log $(W.c/\lambda\ .2v)$ for the theoretical data. Thus, when the plots of observed and theoretical curves of growth are superposed, the difference in the ordinates is a measure of the turbulence in the chromosphere. For the abscissa the observational data are usually laboratory f-values when they are available; theoretical intensities calculated from the sum rules can be used if necessary. In the theoretical plot the abscissa, log X_0 contains terms involving the abundance of the atom being studied, the lower excitation potential, the excitation temperature and the turbulent velocity. Plots are made for all lines of a given atom, such as Fe I, having approximately the same lower excitation potential. Each plot is superposed on the theoretical set of curves of growth. The mean displacement in the ordinates of these plots is a measure of the turbulent velocity. The displacement in the abscissa is a function of the excitation potential from which the excitation temperature can be derived.

For many years the best laboratory f-values for Fe I were considered to be the measures of King and King (1938). However, doubts have been cast on the temperature the Kings used for their electric furnace and it is now believed that the values can be improved. In order to check some of the data for the chromospheres of the eclipsing stars, the Fe I f-values used by Foy (1972), May et al. (1974) and by Bridges and Kornolith (1974) were plotted against Wright's (1959) data for 31 Cygni. The plots for each excitation potential were combined and mean observational curves of growth for each spectrum were fitted to the theoretical curves. While the results were not exactly the same as those originally published and the new f-values did not give an exact 1 : 1 correspondence with King's data, the differences were relatively small over the wavelength range covered (3700 - 4500 Å) and the conclusions concerning turbulence and temperature based on the King f-values do not seem to require major revision.

Published turbulent velocities agree that the chromospheric lines observed in the atmospheres of the ζ Aurigae stars show considerable turbulence. For ζ Aurigae, Wilson's (1960) summary notes that the microturbulence is between 5 and 15 km/sec., though some of the earlier, lower-dispersion data give values up to 20 km/sec. There is some evidence that the turbulence and also the excitation temperature increases with height in the atmosphere, and also that the value for ionized lines may be a few km/sec. greater than for neutral atoms. Effectively the same conclusions were reached by Wright (1959) for 31 Cygni.

A preliminary study of the Victoria high-dispersion spectrograms of 31 Cygni obtained at the 1971 eclipse has been begun (Morbey et al. 1975). A computer program was prepared to derive the spectrum of the B-type star by subtracting the spectrum of the K-type star, obtained during totality, from the composite spectrum observed far from eclipse. This program proved to be quite satisfactory and several helium lines could be observed on computer-constructed tracings in the spectrum of the B-type star that had not been detected previously. Some work has been done on the spectra obtained during the chromospheric phases of this eclipse, but the intensities have not been studied yet.

THE STRUCTURE OF THE CHROMOSPHERE

Several theories concerning the structure of the chromosphere of the ζ Aurigae stars have been suggested but the final solution probably has not yet been found. The Mount Wilson observers considered that the radiative flux from the B star is likely to be the chief source of the chromospheric excitation but found that, with a smooth density distribution, the B star should ionize the metals much more than has been observed; they concluded that the chromosphere must contain condensations sufficiently dense to prevent excessive ionization by the B-star radiation. Later Magnan (1965) discussed deviations from local thermodynamic equilibrium for ionized calcium with a three-level model atom and a continuum; he considered that the observations for 31 Cygni could be reconciled, taking electron collisions into account, with a homogeneous atmosphere where the average number of electrons is 10^{10} and the effective temperature is 10,000° K. As noted above, Saito discussed the effects of hydrogen Lyman quanta from the B star on ionization and shock-wave fronts in the K-type chromosphere and concluded that the hydrogen velocities observed near eclipse could be explained by such fronts combined with a slow rotation of the K-type star. Groth (1957) earlier had suggested that the source of super excitation required to produce the excitation and ionization in the chromosphere lies in the ultraviolet radiation from the transition zone between the chromosphere and the corona where the turbulent energy is dissipated. During the past few years Bernat, Boesgaard, Linsky, Reimers and others have been studying the chromospheres and circumstellar matter surrounding late-type stars and their model calculations may well be adaptable to conditions in the atmospheres of the giant components of the ζ Aurigae stars.

Very recently Stencel et al. (1979) were able to obtain observations of the 32 Cygni system with the IUE satellite in the region 1150 - 3200 Å at phase 0.2, a few months after eclipse. They observed numerous ionized lines of silicon, iron, magnesium, etc. with P Cygni type profiles (emission peaks at the redward edge of the absorption lines). The profiles of the strong lines showed absorption components of - 200 km/sec. and even up to - 400 km/sec., similar to, but with higher velocities than those previously observed only for the Ca II line near eclipse. They suggest that the Fe II emission lines would probably dominate the 2330 - 2630 Å range during the chromospheric phases and this emission would explain the excess radiation observed at that time by Doherty et al. (1974). The observed width of the Mg II lines and the strength of the Fe II emission lines combined with the lack of high-excitation lines of C IV and He II lead the authors to suggest that the underlying chromosphere of 32 Cygni may be qualitatively similar to the outer atmospheres of late-type supergiants like α Orionis. They conclude, from the observed strong P Cygni-type profiles, that the B star lies within the upper chromosphere of the K-type supergiant, and that the ionizing radiation from the B star penetrates into the supergiant atmosphere and sets up moving shock fronts within the chromosphere.

We have mentioned very little about VV Cephei in this paper although it clearly shows chromospheric lines at the time of eclipse. Although Goedicke (1939) and Peery (1966) made some analyses of the atmosphere, their data were not sufficient to give better than approximate results. Peery did estimate a turbulent velocity of 48 km/sec from his curve-of-growth data, but the value has not been verified.

At Victoria, spectra of VV Cephei have been obtained over a full cycle. The analysis of the Hα profiles and a determination of the orbit has been completed by Wright (1977). Most of the plates have been measured for radial velocity to determine which lines arise in the two stars and which are produced in the circumstellar envelope, but it has not yet been possible to analyze the intensities. Prior to the 1957 eclipse McKellar et al. (1957) studied the changes in the Ti II lines at 3759 and 3761 Å. These lines showed at least two components at -38 and +16 km/sec. with a suggestion of emission between them, especially close to totality. A preliminary study of these lines from 1975-78 show that these lines are present at the next eclipse - but they also appear with somewhat different velocities and intensities throughout the cycle. Thus it would appear that they are at least partially circumstellar in origin. The Victoria observations of the chromospheric phases of the 1976-77 eclipse were obtained in the region 3400 - 4250 Å in order to minimize the effect of the M-type star. Many of the plates could be stronger but they should be useful for the analysis of some phases of the chromosphere.

Much more information remains to be gained from observations of the ζ Aurigae stars. With modern techniques it is possible to obtain profiles of individual lines, such as the K line, much more accurately and probably in less time than with photographic plates, but when large regions of the spectrum are to be examined at a given phase, as is desirable for these stars, the photographic method would still seem to be most useful.

In this review we have examined the pertinent data obtained from plates of the ζ Aurigae stars observed near the time of their eclipses. Radial-velocity measurements show that there is probably some kind of chromospheric equatorial current that is superposed on the slow rotation of the star. The ionized calcium lines show that there must be large clouds or prominences, sometimes moving faster than the escape velocity, that can be observed for several days. Satellite data may well show that the early-type star that we have become accustomed to call a "probe" may be close enough to seriously affect conditions in the late-type supergiant star whose atmospheric structure we have hoped to determine - hence this structure may not be that of a normal single star. Modern theories of radiative transfer and line formation may give new clues concerning this structure based on the observational data obtained for these stars. It has been suggested that the microturbulent velocities assuming curves of growth based on pure absorption are merely the result of inadequate theory. I cannot answer this question, but it does seem that, for giant stars such as these, velocities up to 10 or more km/sec. would seem to be reasonable for the small-scale motions in the atmosphere, and the macroturbulent velocities for large-scale motions derived from the profiles of up to twice that value also seem to be plausible.

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