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ASTRONOMY AND ASTROPHYSICS

Optical spectra of ζ Aurigae binary systems

I. The 1987 eclipse of ζ Aurigae

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Abstract. In presenting the first results from a joint Cambridge-Hamburg investigation of eclipsing ζ Aur stars, we describe the high S/N, high-resolution observations of ζ Aur which were made at optical wavelengths during its 1987 ingress and total eclipse. The spectra have been analyzed by our method of spectral subtraction, which has enabled us to isolate the spectra of the B star and of the K supergiant chromosphere for the first time in the wavelength region λλ 3650–4650 Å. Over 260 absorption features believed to originate in the supergiant's chromosphere have been identified.

Determinations of the masses, sizes and relative velocity of the component stars enable us to construct a model of the geometry of the eclipse. If the lower chromosphere rotates rigidly with the supergiant, its radial velocity measured at ingress indicates a rotation period that may be synchronous with the orbital period of the system.

Key words: stars: atmospheres of – stars: chromospheres of – stars: individual – stars: binaries: spectroscopic

1. Foreword

The ζ Aur-type binaries, which exhibit the phenomena of atmospheric eclipses, are unique to stellar spectroscopy in providing height resolution of stellar chromospheres. When the line of sight to the B-star secondary in a ζ Aur system passes close to the limb of the occulting K-giant primary, there are superimposed on the composite spectrum additional absorption lines that offer information about the temperature, density, electron density, extent and motion of the K-giant chromosphere. Our ability to observe and isolate the spectra of stellar chromospheres (Griffin, 1988) together with detailed treatment of chromospheric physics (Schröder, 1985, 1986) and stellar winds (Baade, 1988) have been combined in a fresh collaborative effort by members of the Cambridge Observatories, U.K. and Hamburger Sternwarte, G.F.R., to observe and interpret the atmospheric eclipse phenomena of as many ζ Aur-type binaries as possible.

The scope of the project is unfortunately limited by the number of such systems known. Only two (31 and 32 Cyg) show a strong resemblance to ζ Aur itself in consisting of a late-K supergiant and a B dwarf; VV Cep, which was assigned to the ζ Aur group by Christie (1938a), has an M2 Ia primary and shows evidence of much chromospheric activity. Four other systems (22 Vul (Parsons and Ake, 1983), τ Per (Ake et al., 1986), HR 6902 (Griffin, 1986) and HR 2554 (Ake and Parsons, 1987)) have now been classified as ζ Aur types, although the last three have primary stars that are hotter, less luminous and possess notably less extended chromospheres.

A stellar chromosphere is a turbulent transition region between the photosphere, which may be considered the surface of the star, and the corona, from which matter is lost. Outward transport of material from the corona, i.e. the stellar wind, is likely to manifest itself by emission lines of highly-ionized atoms at ultraviolet wavelengths, but not necessarily in a manner that is at all simply related to the temperature and pressure gradients at the stellar surface or in the chromosphere. IUE observations of wind lines in the spectra of various cool giants show incontrovertible evidence (Linsky and Haisch, 1979) that, although most (if not all) such stars are indeed shedding mass, the extent of the chromosphere and the appearance or otherwise of a corona must depend critically upon mechanisms or conditions which are not yet fully understood. Giants which are located close together in the HR diagram, but on opposite sides of the line which marks the division between the types of chromospheres and coronae, may then possess considerably different outer atmospheres: in some the chromosphere is extended and gives way gradually to a cool wind, while others seem to have a small lower chromosphere but a hot corona, with some connecting transition region. Some of the hotter ζ Aur systems lie very near to this dividing line – 22 Vul shows evidence of an extended chromosphere and a cool wind, whilst HR 6902 and (probably) τ Per belong to the class with a small lower chromosphere and a very hot wind. It is hoped that the height-resolved information derived from atmospheric-eclipse spectra of these systems may help to clarify the significance of the dividing line and thereby make an important contribution towards understanding the processes of mass loss.

Our optical investigations have so far included ζ Aur, 22 Vul, HR 6902 and τ Per, which have been observed spectroscopically during their respective ingresses and total or chromospheric

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eclipses. In describing the extraction of chromospheric features from the observations and the subsequent interpretation in terms of chromospheric conditions, we are commencing a series of papers about each object in turn. This first one begins, then, with a description and discussion of observations of the chromospheric spectrum of ζ Aur at its eclipse of 1987 November/December.

In this paper we start with an assessment of the observational evidence, as revealed in the literature, and of the progress in its interpretation. We attempt fresh derivations of the luminosities and masses of the components, and of the geometry of the eclipse.

2. The importance of ζ Aur to stellar physics

ζ Aur was first recognized by Miss Maury (1897) as possessing a composite spectrum, and was subsequently assigned the twin HD numbers 32068 (type K0) and 32069 (type B1) (Cannon and Pickering, 1918). Variations in the radial velocity of the primary were announced by Campbell (1908) and confirmed by Kustner (1914), prompting Harper's systematic study which culminated in the publication (1924) of a spectroscopic orbit whose elements have required but trivial modifications in 65 years. Harper drew attention to the fact that on one plate, taken when the K star in its orbit was in front of its companion, the spectrum of the system was markedly different from usual in that the characteristic "washed out" appearance of the K-giant spectrum had vanished, and instead the K-type absorption lines were particularly intense; although rating the probability of an eclipse in a long-period (972-day) orbit as necessarily small, Harper had indeed recorded just such an event. Bottlinger (1926) forthwith computed the dates of succeeding eclipses, and his predictions were confirmed by photometry at the 1931/32 eclipse (Schneller, 1932a, b, c; Guthnick and Schneller, 1932). Menzel (1936) demonstrated that the shape of the partial-eclipse light curve could be attributed to atmospheric extinction rather than to actual occultation. The first recognition of a chromospheric eclipse should probably be credited to Guthnick (1932), who described variations in the strength and width of the Ca II K-line during the two weeks following totality, and grasped the significance for stellar physics of such a phenomenon.

Successive reviews of the ζ Aur literature have been given by Schneller (1935), Wellmann (1939), Wilson (1960) and Wright (1970). Sahade and Wood (1978) summarized the optical observational evidence immediately before the commencement of IUE research, whereas the information that has accrued about ζ Aur systems from IUE spectra has been reviewed by Hack and Stickland (1987).

Although the steady improvement with the passage of time in the accuracy and range of measurements has not always been matched by a corresponding increase of confidence in the interpretations, Pettit (1948), Roach and Wood (1951, 1952) and Wood and Blitzstein (1957) proved beyond doubt that the eclipse photometry represented an atmospheric as well as a bodily eclipse: the shape of the partial-phase light curve, and in particular the evident wavelength-dependence of the duration of partial eclipse, could be satisfactorily explained by cumulative weakening of the B-star flux resulting from the many absorption lines which develop as the line of sight to the B star approaches the photosphere of the K star.

In major spectroscopic studies Wilson (1948), Wilson and Abt (1954) and Groth (1955, 1957) investigated the properties of both the chromosphere and the photosphere of the K supergiant. Rather little attention has been directed to the chemical constitution of the supergiant, though its photospheric abundances are not very dissimilar from those of the Sun: the ratio of metals to hydrogen has been found to be lower by a factor of 3 (Groth, 1955) or higher by 0.1 dex (Luck, 1982). The strength of the He I λ 10830 Å line has been described as small (30 mÅ) but possibly variable (Zirin, 1982).

Radial-velocity measurements of the chromospheric K-line core have been made at several past eclipses. The results, which could not be modelled by simple rotation of the K supergiant and which, according to the likely presence of small satellite K lines (McKellar and Petrie, 1952; Odgers and Wright, 1965), should not be so modelled, have been explained generally as a combination of random and systematic (streaming) motions of condensations of material (e.g. Wilson, 1960, and references cited therein; Saito, 1970) that are possibly associated with an increase in turbulence with height in the lower chromosphere (Wilson and Abt, 1954; Saito, 1965); the specific picture has varied from large-scale solar-like prominences (McKellar and Petrie, 1952) to predominantly downward movements (Faraggiana and Hack, 1966). Changes in the emission reversals of the supergiant's K line (Kitamura, 1967) have also been considered to indicate activity within the chromosphere.

Most optical investigations have concentrated on the ultraviolet spectral region – in the cases of Wilson (1948) and Wilson and Abt (1954), the far optical ultraviolet, down to λ3150 Å – where the spectra of both stars are visible and where the effects of chromospheric absorption are plentiful. However, observations taken during egress of the Hα region of the K supergiant (Saito, 1973) also revealed a phase-dependent phenomenon: strong satellite absorption lines of Ca I λ6572 Å were reported on three successive days just after fourth contact, and were attributed to a circumstellar cloud that was expanding with a velocity of about 100 km s^{-1}. A repetition of the observation at the next eclipse (Saito and Kawabata, 1976) again revealed the satellite lines but weaker in strength and displaced by only a quarter of the velocity seen on the previous occasion. There seemed doubt about the presence of simultaneous satellite features associated with Ca I λ4227 Å, though their detection would have been harder on account of the relative weakness of the K star at that wavelength.

The advent of IUE in 1978 revolutionized research into this and other ζ Aur systems. IUE spectra revealed a multitude of emission lines (Chapman, 1980) representing the outward flow of material from the K supergiant (Stencel and Chapman, 1981). At IUE wavelengths the K-star flux may be considered to be negligible compared with that of the B star, so the compositeness of the system's spectrum is of no consequence. On the other hand, the absorption spectrum of the B star is so rich, and chromospheric features, when they are formed, are optically thick and are so strong, that line blending is a serious factor and limits the usefulness of chromospheric eclipse spectra at IUE wavelengths, whereas blending is less severe at optical wavelengths and the astrophysically weaker lines that can be measured there provide information about the lower layers of the chromosphere. Thus the optical and IUE observations are mutually complementary insofar as they relate to chromospheric spectra; IUE spectra also show the coronal (wind) emission lines but optical spectra include the Balmer series. In view of the success of digital subtraction techniques in unravelling composite spectra, a fresh attempt at understanding the optical chromospheric spectra of ζ Aur systems now appears timely.

3. Observations of the ζ Aur system

Spectra of ζ Aur were obtained photographically with the Calar Alto 2.2-m telescope and coudé spectrograph during ingress and totality in 1987 November/December. Exposures of the blue and near ultraviolet spectral regions were made both with the f/3 camera (8.8 Å mm^{-1}) and with the f/12 (2.2 Å mm^{-1}); the projected slit widths were 19 and 23 μm respectively. All spectra were taken on IIa-O plates that had been hypersensitized by baking for 1 hour at 65°C in forming gas. Because of indifferent weather, exposures were only possible on one night during ingress before first contact, on the one night of partial eclipse between first and second contacts, and on two nights during totality. The spectrum of ζ Aur A, which can be observed in pure form only during total eclipse, is essential to the process of unravelling the secondary and chromospheric spectra taken outside totality; and since a subtraction of two spectra reduces the signal but sums the noise it is important that the totality spectra should have as high S/N as possible. In good weather conditions we would have taken multiple exposures of ζ Aur A with both cameras; in the event we could only take one plate with the f/12 camera, and it was weaker than optimal at wavelengths less than about λ3800 Å. A list of the spectrograms is given in Table 1, and some are reproduced in Fig. 1. We have also included three other spectrograms that were taken at phases well outside eclipse; they are very important for the derivation of the spectrum of the B star.

Table 1. Spectrograms of ζ Aur

Plate number	Date (UT)		Width (mm)	Phase of eclipse
Ce 24156	1984 Mar	23.15	2.6	Outside eclipse
S 3616 a	1987 Nov	15.89	2.4	Ingress, chromo-
S 3616 b		15.91	2.4	spheric eclipse
L 3617		15.97	2.4	
L 3618		16.00	1.2	
L 3619		16.17	2.4	
S 3622		16.92	2.4	Partial eclipse
L 3623		17.07	2.4	
S 3624 a		17.18	2.4	
S 3624 b		17.21	2.4	
L 3628		19.08	2.4	Total eclipse
S 3642 a		19.21	2.4	
S 3642 b		19.24	2.4	
S 3644 a		30.94	2.4	
S 3644 b	Dec	1.01	2.4	
S 3644 c		1.04	2.4	
L 3980	1988 Sep	27.13	2.4	Outside eclipse
S 3985		28.10	2.4	

Notes: All plates except the first were taken with the coudé spectrograph of the 2.2-m telescope at Calar Alto Observatory (DSAZ). Those with prefix 'L' were taken with the f/12 camera, and have a dispersion of about 2.2 Å mm^{-1}; those with prefix 'S' were taken with the f/3 camera and have a dispersion of about 8.8 Å mm^{-1}. Plate Ce 24156 was taken with the 32-inch camera and coudé spectrograph of the Mount Wilson 100-inch telescope, and is comparable with the Calar Alto 'S' plates.

Stellar spectra were widened as much as possible within the limits set by the spectrograph characteristics and available exposure times. At the coudé focus of the 2.2-m telescope a rocking plate is provided for widening spectrograms, but in respect of the f/3 camera its range is unfortunately restricted to 1 mm which is substantially narrower than optimal. We therefore widened our spectra by trailing the star image repeatedly along the entrance slit; the usual trailing rate was one slit length in about 4 minutes. Rather than use an image-rotator, with its attendant light-losses, to maintain a convenient orientation of the coudé field, we instead calculated the necessary rate offsets in both right ascension and declination and entered them at the telescope control panel. We altered the offsets about every 20 or 30 minutes in response to the rotation of the field with changing hour angle.

Spectrophotometric calibration for the Calar Alto coudé spectrograph is offered by the use of a Lyot birefringent filter, but after experiencing difficulties with that equipment (Griffin, 1989) we fetched our own auxiliary calibration spectrograph (Griffin, 1979) from Mount Wilson and relied solely upon that. In its original form the auxiliary spectrograph had a multiple slit composed of 24 elements of different widths; five of them, distributed across its length, had nominally the same width and provided a built-in check of the illumination of the slit as a whole, while two were closed so as to indicate the level of the 'clear plate' background. For service at Calar Alto the auxiliary spectrograph was supplied with a new multiple slit that was manufactured more accurately by etching. The apertures of the new slit are mutually separated instead of being juxtaposed as in the original slit. The difference may be appreciated by comparing transmission scans across spectrograms taken with the new slit (Fig. 2) and the old one (Fig. 2 of Griffin, 1979): the new spectrograms show 22 calibration strips alternating with regions of clear plate. It is now practical to assess the transmissions of the calibration strips by computer and to derive the calibration curves automatically; the only input required is the set of incident intensities, i.e. the widths of the various slits.

The stellar spectrograms were traced in steps of 5 μm with a digital microphotometer. The establishment of calibration curves and the generation of direct-intensity spectra at linearized wavelength intervals of 50 mÅ in 200-Å 'pages' has been described elsewhere (Griffin, 1979; 1986) and constitutes what we refer to as our standard routine. A modification to that routine was made in respect of the high-dispersion plates, from which intensities were derived every 10 mÅ and in pages 50 Å long. All of the five medium-dispersion exposures taken during totality, and therefore showing ζ Aur A alone, were averaged, and so was – in the first instance, though without discarding irretrievably the individual records – each pair of ingress spectra taken during one night (S 3616 a and b, and S 3624 a and b) and the trio of high-dispersion spectra (L 3617–19).

4. Spectra of the chromosphere of ζ Aur

4.1. Isolating the spectra

The spectrum of ζ Aur A can be observed in isolation during the eclipse of the B star, but the spectrum of ζ Aur B can never be seen

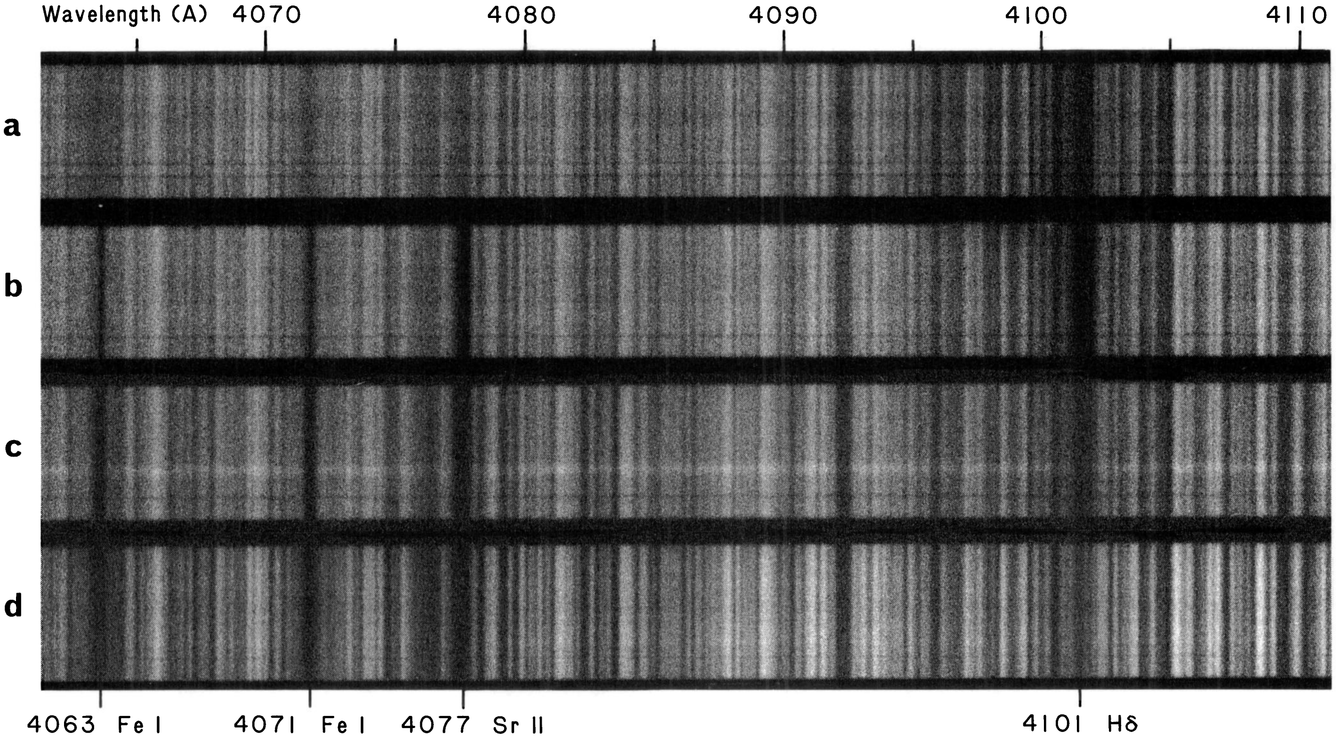

Fig. 1a–d. Small parts of four spectrograms of ζ Aur taken with the f/12 camera (2.2 Å mm^{-1}) of the coudé spectrograph of the Calar Alto 2.2-m telescope. **a** 1988 Sept. 27.1, showing the normal composite spectrum far from eclipse. λλ 4063, 4071, 4077 Å, lines that are strong and broad in the late-type spectrum, have a washed-out appearance owing to the presence of the quasi-continuous spectrum of the B star. On the other hand, the Hδ line in the B-type spectrum is visible as a broad hazy absorption. **b** 1987 Nov. 16.1, during atmospheric eclipse. There are intense narrow cores, caused by absorption of the B-star light in the K-star chromosphere, in λλ 4063, 4071, 4077 Å. **c** 1987 Nov. 17.1, early in partial eclipse. The chromospheric cores are wider than on the previous night. **d** 1987 Nov. 19.1, in total eclipse. The chromospheric cores have disappeared but the contrast of the whole spectrum has increased, because the underlying B-star continuum has gone, as has the broad Hδ absorption

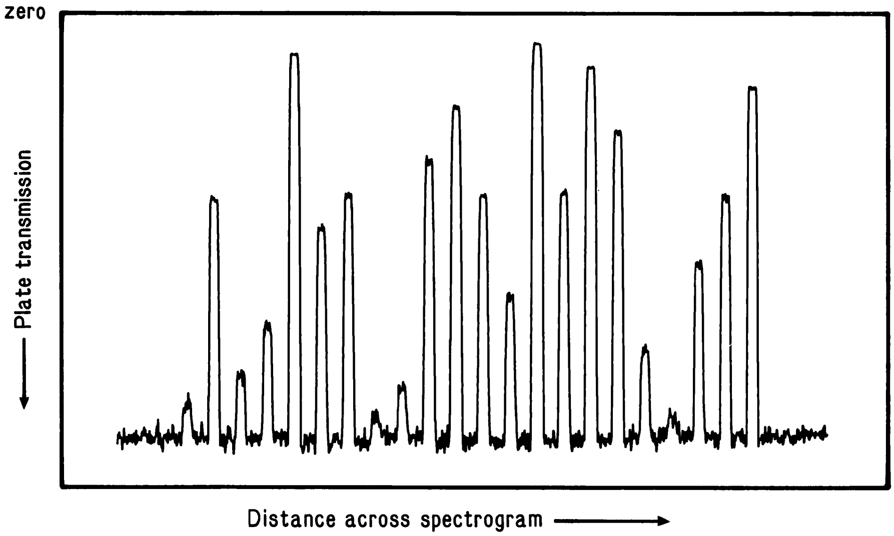

Fig. 2. Density tracing across a calibration exposure, plotted with plate transmission increasing downwards from zero at the top of the diagram. The multiple entrance slit of the calibration spectrograph is composed of 22 mutually separated slits of known widths I_i, which all receive light from a uniformly illuminated white surface. They give a series of continuous spectra whose relative intensities are simply proportional to the values of I_i. Those values were chosen at equal intervals of 0.1 in the logarithm; one particular value, near the middle of the range, is replicated at intervals along the slit to provide a built-in reassurance of the uniformity of illumination and processing on every plate. The photometric calibration curve is obtained at any wavelength by plotting the observed transmissions of the images of the various spectra, traced perpendicularly to the dispersion, against the corresponding values of $\log I_i$

alone. It can, however, be recovered from the composite spectrum by a process of subtraction first demonstrated by Lee and Wright (1960). In our application of the process, the correct fraction of the relevant (medium- or high-dispersion) spectrum of ζ Aur A observed in totality was subtracted point by point from each composite spectrum, thereby revealing spectra of ζ Aur B with the superposed chromospheric absorption lines. Details of the techniques that have been developed for determining what may be the best fraction of the primary (or, in the case of a non-eclipsing system, the surrogate) spectrum to subtract have already been given (Griffin, 1986); in a system such as ζ Aur, whose component spectra are quite different, the null method of cross-correlating the residuum with a primary-like spectrum in order to assess that fraction should work fairly well. Examples of subtractions performed with both medium- and high-dispersion spectra are illustrated in Fig. 3.

The subtraction procedure demands that the two spectra prepared for subtraction be aligned very carefully in order to avoid artificial 'P Cyg' profiles in the residual spectra. The practice of determining a wavelength scale by applying the grating equation to a suitably selected set of identified stellar lines and employing the same standard lines as far as practicable for all spectra should ensure a good correspondence between the wavelength scales in different spectra. Infelicities can, however, occur, particularly where the number of useable and well-defined lines has had to be drastically reduced for some reason. The standard lines will by definition be features in the late-type stellar spectrum if that is the chosen rest-frame for the wavelength scale; but if the

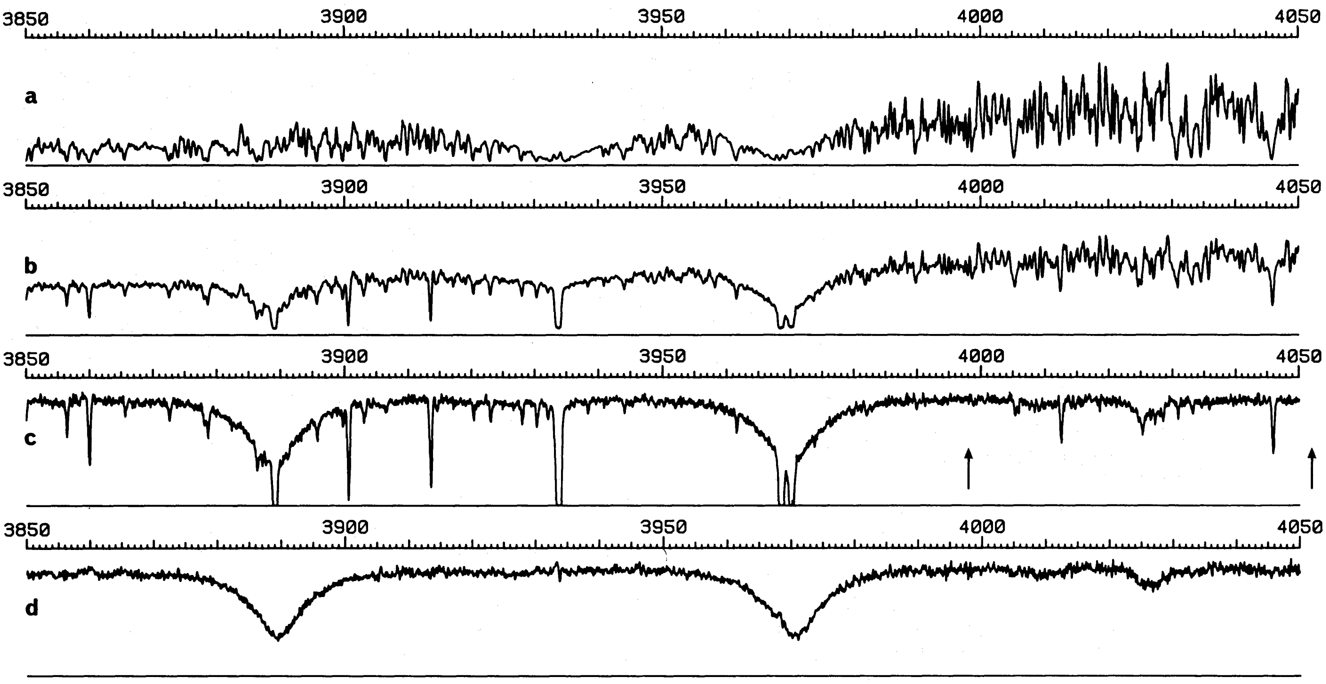

Fig. 3a. Subtraction of the spectrum of ζ Aur A (panel a, observed during total eclipse) from the composite spectrum of the ζ Aur system (panel b), observed during ingress on 1987 Nov. 15.9, reveals the spectrum of ζ Aur B with superimposed chromospheric lines (panel c). The chromospheric features are intrinsically very narrow, in contrast to lines in the spectrum of ζ Aur B (panel d). The spectra in this figure have original reciprocal dispersions of about 8.8 Å mm^{-1} (panels a–c) and 10 Å mm^{-1} (panel d). The region between the arrows is the subject of Fig. 3b

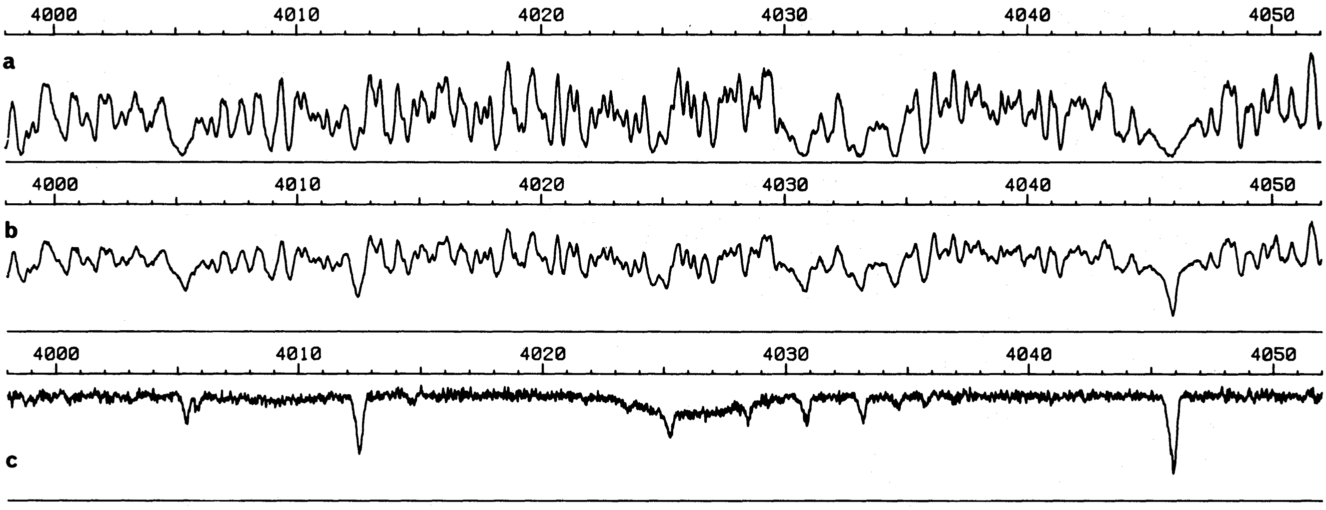

Fig. 3b. Subtractions similar in nature to those in Fig. 3a, but based upon higher-dispersion spectrograms (2.2 Å mm^{-1}). The total-eclipse spectrum (panel a), is subtracted from the composite spectrum observed during ingress on 1987 Nov. 16.1 (panel b), to reveal chromospheric features superimposed on the spectrum of ζ Aur B (panel c), which consists largely of continuum but also includes very broad He I lines (altogether invisible in panel b) at λλ4009 and 4026 Å

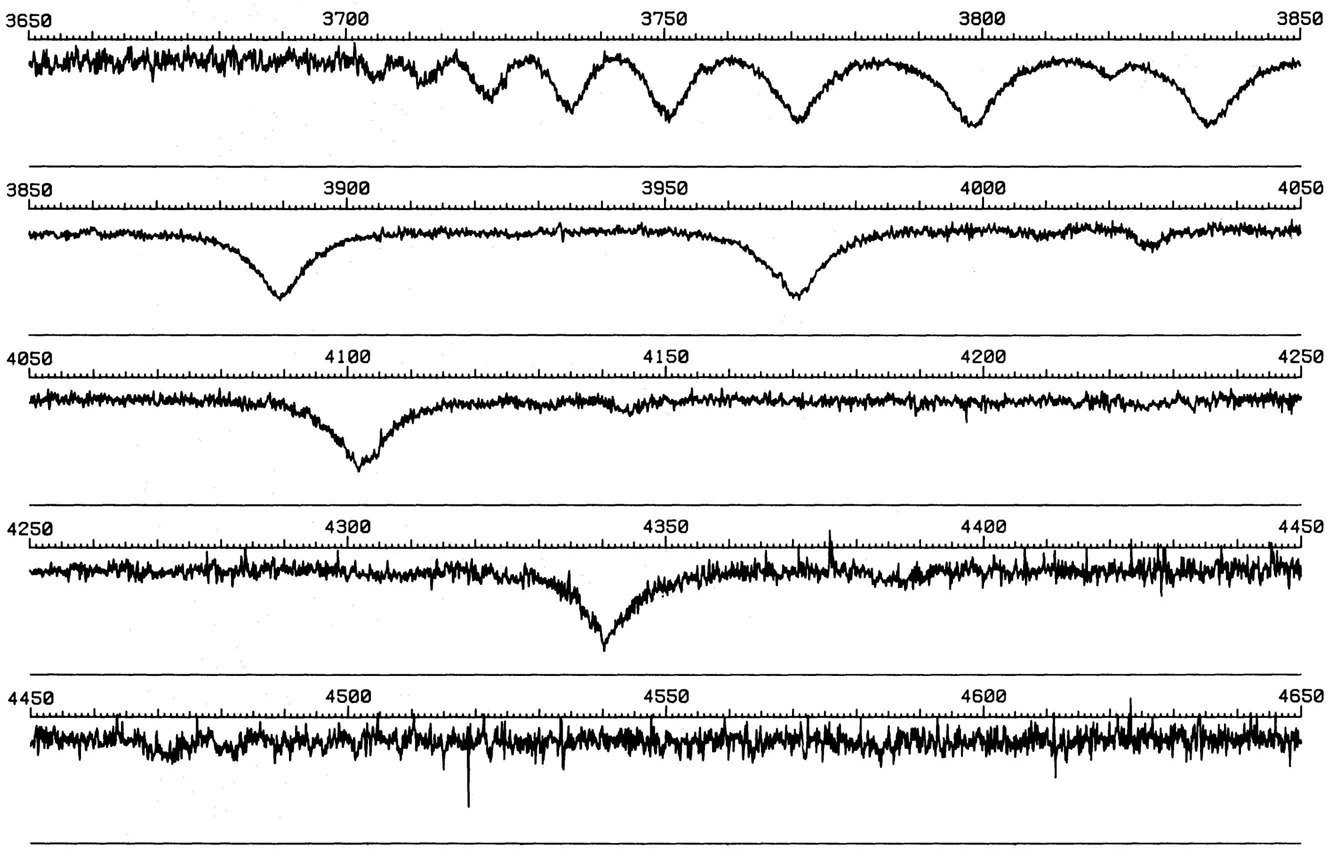

Fig. 4a. Spectrum of ζ Aur B far from eclipse, obtained by subtracting the total-eclipse spectrum (observed with the medium-dispersion Calar Alto camera) from the composite spectrum observed at Mount Wilson at a phase about 363 days (0.37 P) before eclipse

contrast of the late-type spectrum is greatly lowered by the overlying continuum of an early-type companion, or particular lines are blended with or disguised by chromospheric features, or give unacceptable residuals for any other reason, the number of lines remaining to define the wavelength scale may become dangerously small and the scale derived from them can be unacceptably warped. It is always possible to force a particular wavelength scale by fixing the value of the camera focal length (normally a free parameter in the solution of the grating equation) and anchoring the scale to one particular standard line, though thereby assigning any error in the definition of that one line to the whole scale. In other cases the deleterious effects of the above difficulties upon the wavelength scale may be more insidious, since there may be only a few useable standard lines in a 200-Å stretch, and errors in the scale can pass undetected if the wavelength residuals are fortuitously small.

The ζ Aur subtractions exemplify all these problems, and also place an additional strain upon the accuracy of our wavelength scales on account of the inherent sharpness of the lines in the spectrum of the giant: the narrower the line, the fewer 50-mÅ points define it and the more noticeable is the effect of even a very minor scale misalignment. Evidence of small but non-negligible misalignments showed up in the subtracted chromospheric spectra of ζ Aur B in the form of enhanced noise in some part of a 'page'. We sought to minimize such effects by applying small, wavelength-dependent displacements amounting to 5 or 10 mÅ between the two wavelength scales before subtraction. Any ambiguity built into the reference wavelength scale by this treatment was considered to be justified by the improvement in the appearance and photometric determinacy of the subtracted spectra. A possible explanation for the implied annelid-like behaviour of the spectra may be found in the method used for drying the photographic emulsions. A wet emulsion shrinks slightly as it dries, so if it dries non-uniformly the emulsion tends to be pulled towards the areas that dry first, carrying the image with it. In the past, at other observatories, it has been our practice to dry spectrograms by standing them on end with the spectra almost vertical: drying progressed evenly down the length of emulsion in the direction of the dispersion, and the effect of any shrinkage would have been virtually constant in that direction. At Calar Alto, on the other hand, there are drying racks which hold the spectrograms on edge but with the spectra horizontal, so the moisture, caused by surface tension to 'pool', drained across the spectra in a number of separate streams during drying and probably brought about small variations in the regularity of the emulsion over regions of the order of 1 or 2 cm wide. We should emphasize that the overall effects are indeed tiny, and that it required a sensitive test such as was afforded by the ζ Aur subtractions to show them up. Alerted during 1989 to these possibilities, we reverted to the former scheme for drying plates, so we may hope that the latest spectrum of ζ Aur (S 3985) should be free from any significant emulsion shifts; however, we continue to rely upon the 1987 eclipse spectra for the primary spectrum, so the application of spectrum shifts is still required.

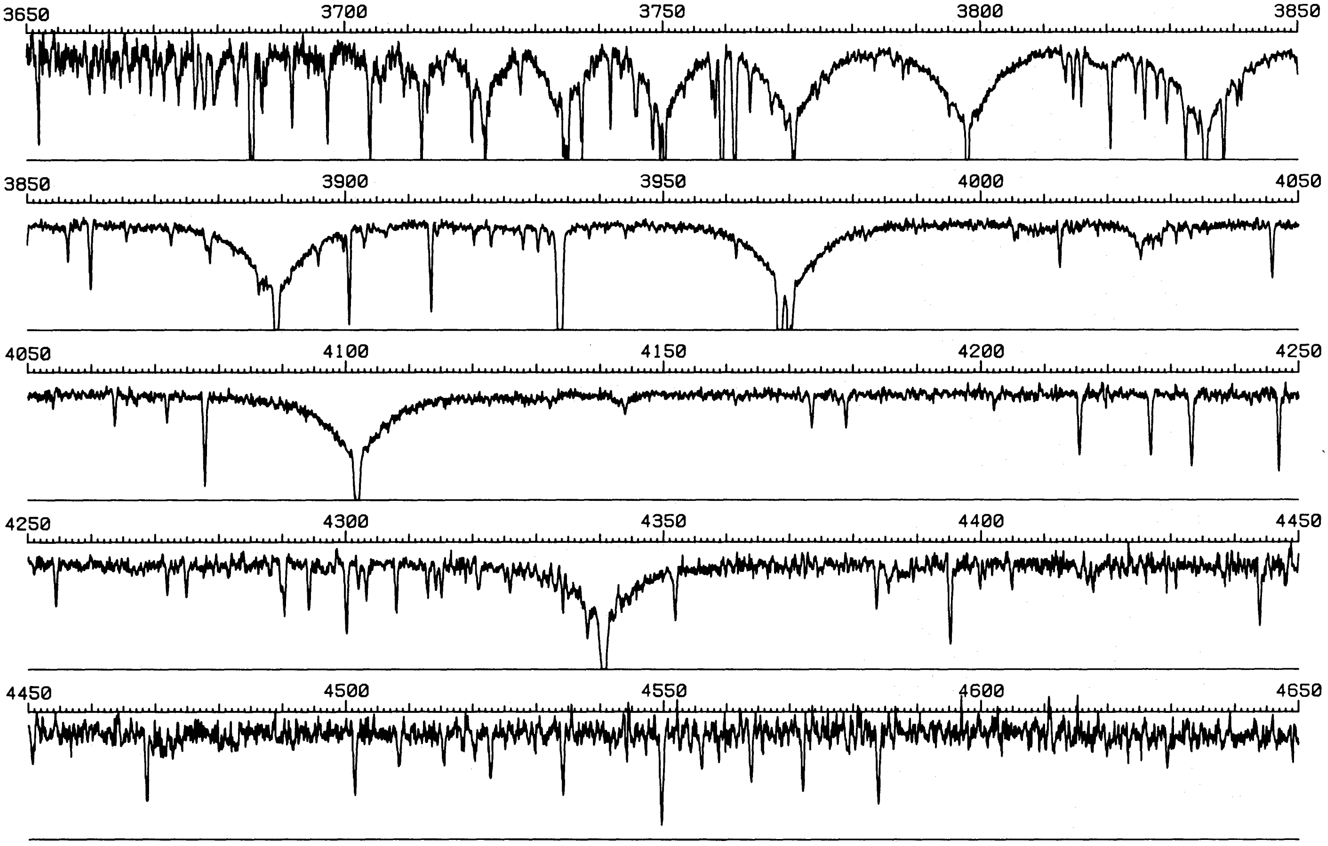

Fig. 4b. Spectrum of ζ Aur B corresponding to that in Fig. 4a but showing the superposed chromospheric lines. The total-eclipse spectrum observed with the medium-dispersion Calar Alto camera has here been subtracted from the composite spectrum observed with the same equipment on 1987 Nov. 15.9, less than a day before first contact in the eclipse

In Fig. 4 we show the spectra of ζ Aur B, (a) far from eclipse and (b) during atmospheric eclipse and showing superimposed chromospheric lines. Figure 4a was derived by subracting the medium-dispersion total-eclipse spectrum from Ce 24156, which had been obtained far from eclipse (phase .54) with the 32-inch camera of the coudé spectrograph at the Mount Wilson 100-inch telescope. Although the characteristics of Ce 24156 are quite similar to those of spectrograms taken with the f/3 system at Calar Alto, slight differences in the resolution, dispersion, and intrinsic instrumental profiles of the two spectrographs called for the application of small wavelength-dependent blurring corrections in order to make the two spectra match properly. It has to be remarked that subtractions are facilitated when the spectra in question have been obtained with the same spectrograph. Figure 4b was derived from the medium-dispersion spectrogram S 3616 taken on 1987 November 15.90.

Figure 5 shows the whole spectral region covered by our higher-resolution spectra taken during atmospheric eclipse (averaged from plates L 3617 to 3619). Owing to the weakness of the total-eclipse spectrum of ζ Aur A the cores of strong chromospheric lines below about λ3800 Å exhibit abnormal noise because the fluxes in both source spectra are so small. All subtracted spectra also show rather low S/N ratios for $\lambda \gtrsim 4400$ Å, where the B-star flux is small relative to that of the supergiant. However, a comparison between Figs. 4b and 5 reveals detailed reproducibility, even of weak lines that appear as relatively fine features on the medium-dispersion spectrum, and encourages confidence in the use of the f/3 system for stars that are too faint to be observed with the f/12 camera.

Initially, chromospheric spectra were derived from the three high-dispersion spectrograms (L 3617, L 3618 and L 3619) separately. Their mid-exposures spanned an interval of $0^{\mathrm{d}}.2$, during which (according to section 5.3) the B star had moved through a distance of about 1/7 of its diameter nearer to the supergiant. Superposition of tracings of the individual chromospheric spectra revealed a general, though very slight, strengthening of the features during that interval; however, since the effects were so tiny and scarcely significant compared with errors in measuring equivalent widths, it was felt that the benefits of increased S/N obtained by averaging the spectra outweighed the possible astrophysical value of handling the spectra individually.

We should comment on the difficulties experienced in respect of the spectrum taken during partial eclipse (L 3623). During that phase the line of sight to the visible part of the disc of the B star passes very near to the K star, through layers where the low chromosphere is merging with the photosphere. The observed spectrum reflects that fact: instead of a K-supergiant spectrum, washed out by the companion's flux as in the ordinary composite case but supplemented by individually enhanced chromospheric lines, we see a strong spectrum which resembles that of the K star but which shows even greater contrast; in terms of line positions it appears almost indistinguishable from that of the photosphere.

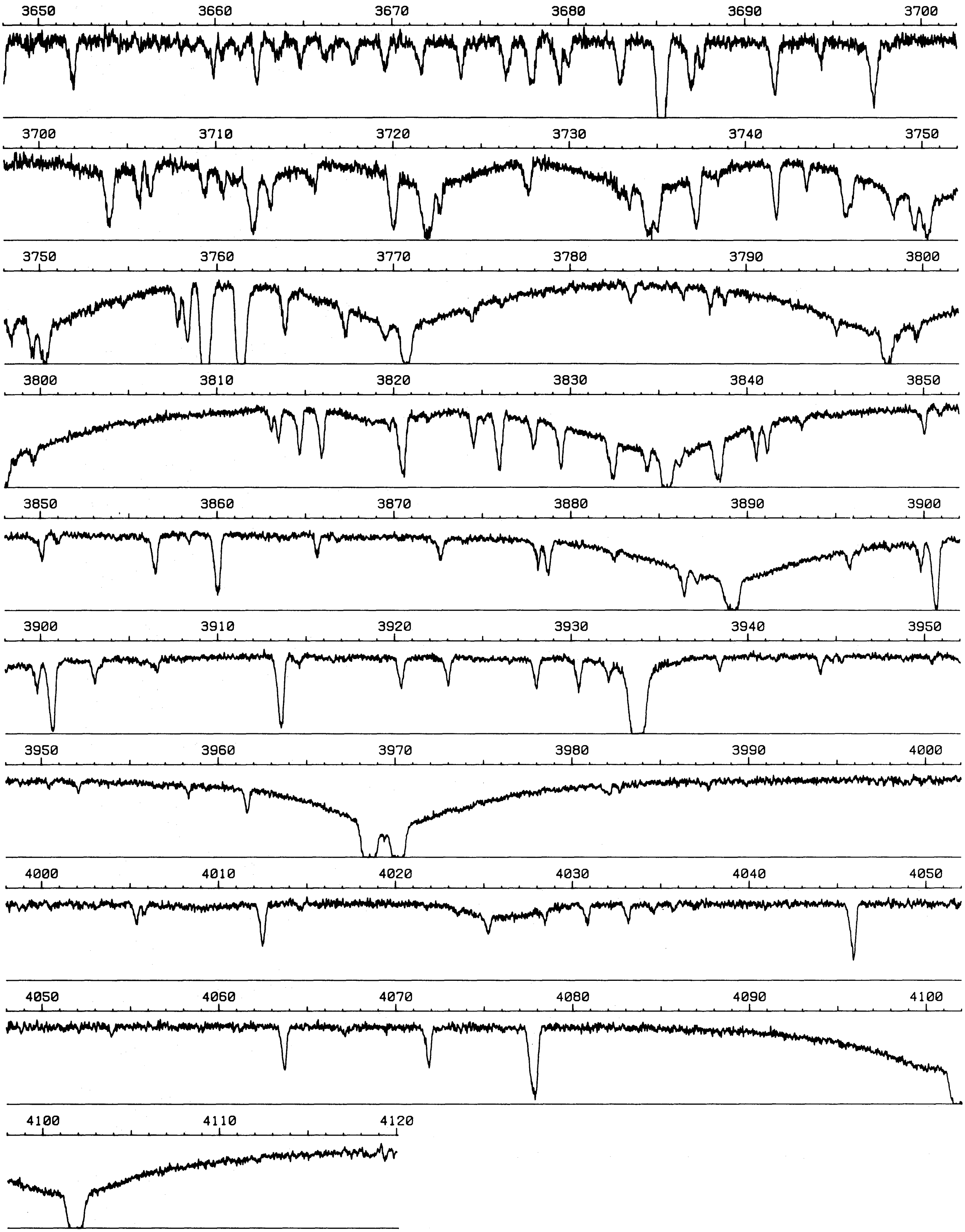

Fig. 5. Detailed chromospheric spectrum seen against ζ Aur B, observed at high dispersion at Calar Alto on 1989 Nov. 16.1. The spectrum of ζ Aur A, photographed with the same equipment during totality, has been subtracted from the actually-observed composite spectrum

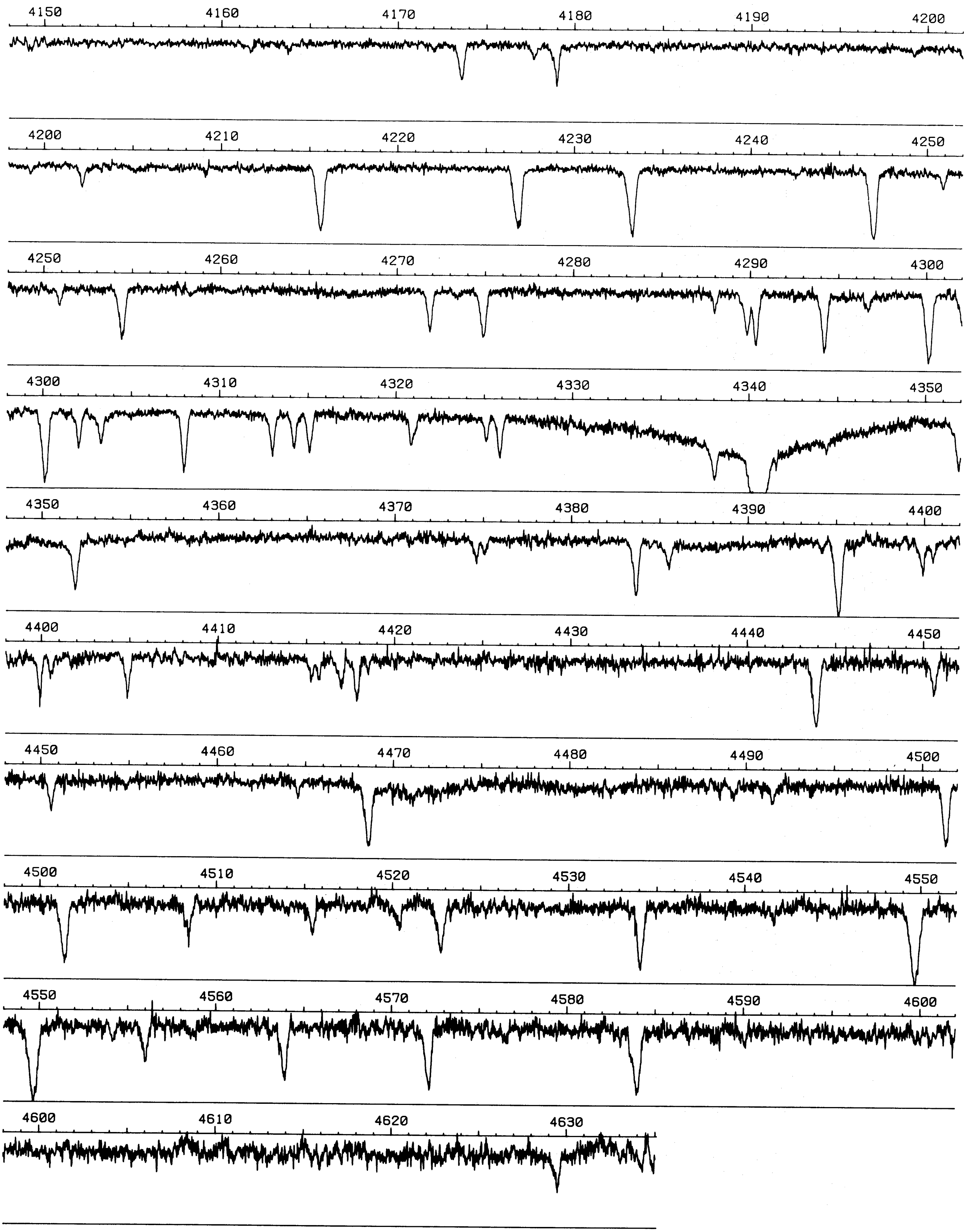

Fig. 5 (continued)

Since there are no lines that can be uniquely attributed to the photosphere, it is impossible to derive a wavelength scale that reliably represents the rest frame of the K supergiant. Moreover, the criteria for determining how much of the photospheric spectrum to subtract from the observed one fail when the residue is so similar to the spectrum being subtracted. Therefore, despite the richness of the absorption spectrum on L 3623 only the region below λ4000 Å, where we were able to identify certain lines attributable solely to the chromosphere, could be reduced with any confidence. A sequence of spectra, illustrating the enormous increase in complexity of the chromospheric spectrum in the final stages of eclipse ingress, is shown in Fig. 6.

4.2. *Measurements of the chromospheric spectrum*

The positions and residual central intensities of 261 chromospheric features visible in Fig. 5 are listed in Table 2, where most of them are identified. In the present work only the high-dispersion spectra were actually measured, but the lower-dispersion spectra provided an opportunity to monitor the profiles of the B-star lines, which are intrinsically broad and shallow and which might otherwise have been mistaken for continuum at higher dispersion. Table 2 constitutes the basis of Paper 2 (Schröder et al., 1990), in which the equivalent widths of about 100 suitable lines (marked with asterisks) are measured and interpreted in terms of column densities, densities and excitation temperatures.

The chromospheric features visible in Figs. 4–6 may be isolated by dividing out the B-star spectrum, as was done for HR 6902 (Griffin, 1988). However, in the case of ζ Aur the benefit of removing a B-type spectrum, whose lines are so much broader than the chromospheric features, would have been academic only; instead, the B-star spectrum was regarded as the local continuum to which all measurements were referred.

During the subtraction procedure the fluxes being apportioned to each spectrum were summed; the information was recorded as the ratio B/K in bands 50 Å wide.

5. The ζ Aur system

5.1. *The radial-velocity orbit*

The elements of the radial-velocity orbit determined by Harper (1924) have undergone small corrections and refinements from time to time; those published by Wood in 1951 are still the most popular set, and few new velocities have been published or orbits calculated. 24 photoelectric radial-velocity observations of ζ Aur have so far been made since 1981, and we hope to publish an orbit in due course when we have obtained improved coverage of all phases. Meanwhile we have derived an orbit from the photoelectric observations together with all published velocities, though in the event only the Lick observations, made before 1910, and the Victoria ones, published by Harper in 1924, proved to be of sufficient accuracy to contribute usefully to the orbit solution. The new preliminary orbit has a period of $972^{\mathrm{d}}.15 \pm 0^{\mathrm{d}}.13$ and a mass function of $1.01 \pm 0.04\, M_{\odot}$; from it we infer that the transverse velocity of the K star at times of mid-eclipse is $28.5\ \mathrm{km\,s^{-1}}$.

We have compared this orbit with 13 published estimates of mid-eclipse times made at 6 previous eclipses. All could be fitted to within a few hours, which is surprisingly little in view of the uncertainties associated both with the period determination and with the interpretation of the photometric observations (Sect. 5.3); the extrapolated mid-time of the recent eclipse is 1987 Dec. 6.40. Tanabe and Nakamura (1957) and Hardorp et al. (1966) also performed the same exercise, though with different selections of observations from the literature. Both deduced orbital periods that were slightly shorter than the $972^{\mathrm{d}}.16$ given by Wood (1951) and recommended by Wright (1970); the value of $972^{\mathrm{d}}.153$ found

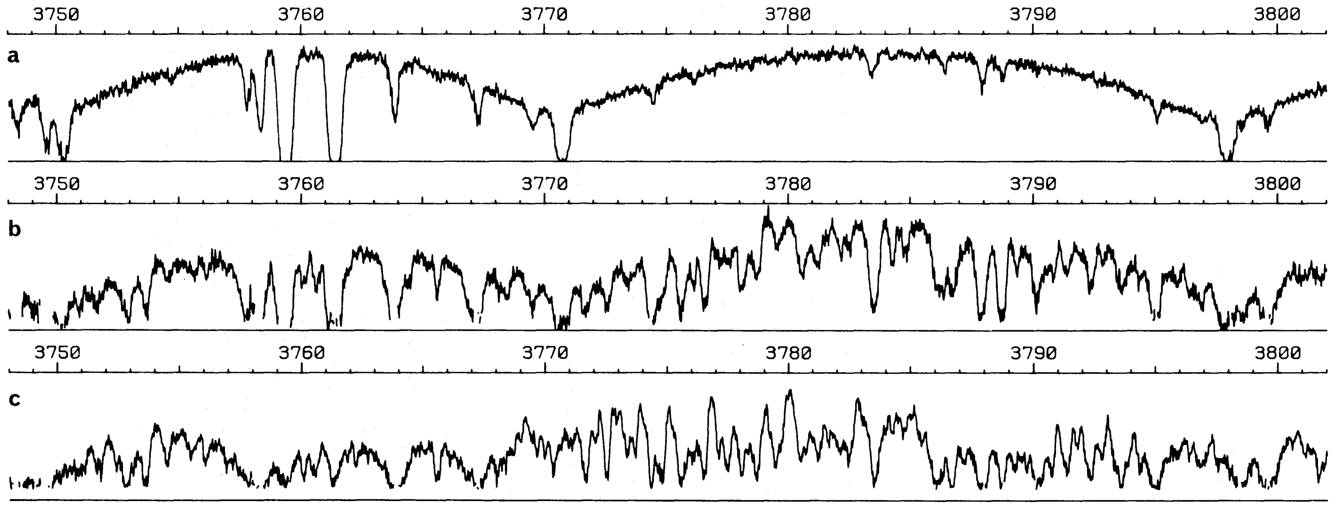

Fig. 6a–c. Sample region of the spectrum of ζ Aur, showing progress into eclipse. **a** (a single strip of Fig. 5) shows the chromospheric lines superimposed on the spectrum of ζ Aur B on 1987 Nov. 16.1, less than a day before first contact; the spectrum of ζ Aur A has been subtracted from the observed spectrum. **b** shows ζ Aur B the next day, during partial eclipse. Again, ζ Aur A has been subtracted away. The broad Balmer lines of the B star are still clearly visible but the chromospheric spectrum superimposed on them has become exceedingly rich and complex. **c** gives the spectrum of ζ Aur A, as observed directly during total eclipse. Gaps in the tracings occur in the cores of certain strong lines where the intensity falls below the photographic threshold of the composite-spectrum and/or total-eclipse exposure

Table 2. Identifications and measurements of chromospheric lines in ζ Aur, seen during eclipse ingress on 1987 Nov. 16.1

λ (Å)	R.M.T.	Lower E.P. (eV)	R_c	λ (Å) (meas.)
3651.68	Cr II 1	2.41	85:	
51.80	Sc II 2	0.01	51:	51.91
57.93	H 35	10.15	87	
* 58.64	H 34	10.15	90	
* 59.42	H 33	10.15	82	59.57
3659.77	Ti II 75	1.57	60	59.88
* 60.28	H 32	10.15	82	
* 61.22	H 31	10.15	84	
62.24	Ti II 75	1.56)	47	
62.26	H 30	10.15		
*3663.41	H 29	10.15	82	
* 64.68	H 28	10.15	70	64.80
* 66.10	H 27	10.15	78	66.21
66.54	Sc II 2	0.02	91	
* 67.68	H 26	10.15	70	67.77
*3669.47	H 25	10.15	67	69.58
* 71.48	H 24	10.15	60	71.62
* 73.76	H 23	10.15	52	73.87
* 76.37	H 22	10.15	56	
77.69	Cr II 12	2.69)		
3677.85	Cr II 12	2.69)	47	
77.93	Cr II 12	2.69		
* 79.36	H 21	10.15	52	79.47
79.67	Ti II 75	1.57	:	
79.92	Fe I 5	0.00	68	
*3682.81	H 20	10.15	45	82.93
* 85.19	Ti II 14	0.59	15:	
* 86.83	H 19	10.15	42	86.93
* 87.46	Fe I 21	0.86	68	87.54
* 91.56	H 18	10.15	36	91.67
3694.19	Yb II 1	0.00	79	
* 97.15	H 17	10.15	26	97.26
98.17	Zr II 71	1.01	91	
*3703.86	H 16	10.15	26	03.96
* 05.57	Fe I 5	0.05	56	05.64
*3706.22	Ti II 73	1.56	58	06.30
07.83	Fe I 5	0.09	93:	
* 09.25	Fe I 21	0.91	63	09.32
10.30	Y II 7	0.18	63	10.36
11.97	H 15	10.15	12	12.07
3712.97	Cr II 12	2.69)	45	
13.04	Cr II 12	2.69		
15.19	Cr II 20	3.09	78:	
15.48	V II 15	1.57	70:	
* 19.94	Fe I 5	0.00	18	20.00
3721.63	Ti II 13	0.57)	12	
21.94	H 14	10.15		
* 22.56	Fe I 5	0.09	57	22.63
27.35	V II 21	1.68)	66	
27.62	Fe I 21	0.95		
3732.76	V II 15	1.56	79	
* 33.32	Fe I 5	0.11	59	33.37
34.37	H 13	10.15	11:	
34.87	Fe I 21	0.86	19	
* 37.13	Fe I 5	0.05	23	37.18
3738.38	Cr II 20	3.09	84	
* 41.63	Ti II 72	1.57	31	41.70
* 43.36	Fe I 21	0.99	69	43.44
45.56	Fe I 5	0.09	36:	
45.81	V II 15	1.55	54	
3745.90	Fe I 5	0.12	:	
* 48.26	Fe I 5	0.11	32	
* 49.49	Fe I 21	0.91	28	49.54
50.15	H 12	10.15	7	
50.88	V II 21	1.67	89:	
3754.59	Cr II 20	3.09	88	
* 57.68	Ti II 72	1.56	56	57.78
* 58.24	Fe I 21	0.95	30	58.30
* 59.29	Ti II 13	0.60	0	
* 61.32	Ti II 13	0.57	0	
*3763.79	Fe I 21	0.99	43	63.85
* 67.19	Fe I 21	1.01	58	
69.46	Ni II 4	3.09	65	
70.63	H 11	10.15	0	
74.33	Y II 7	0.13	74	
*3776.06	Ti II 72	1.57	86	
83.35	Fe II 14	2.27	81	
* 86.33	Ti II 12	0.60	86	
* 87.88	Fe I 21	1.01	73	87.94
88.70	Y II 7	0.10	78	
*3795.00	Fe I 21	0.99	71	
97.90	H 10	10.15	0	
98.51	Fe I 21	0.91	75:	
99.55	Fe I 21	0.95	71	
*3812.96	Fe I 22	0.95	75	13.10
*3813.39	Ti II 12	0.60	61	13.52
* 14.58	Ti II 12	0.57	44	14.70
* 15.84	Fe I 45	1.48	43	15.95
19.67	Eu II 1	0.00	88	
* 20.43	Fe I 20	0.86	22	20.52

λ (Å)	R.M.T.	Lower E.P. (eV)	R_c	λ (Å) (meas.)
*3824.44	Fe I 4	0.00	55	24.53
24.91	Fe II 29	2.57	86:	
* 25.88	Fe I 20	0.91	25	25.98
27.83	Fe I 45	1.55	60	27.94
* 29.35	Mg I 3	2.70	36	29.47
*3832.30	Mg I 3	2.70	23	32.41
* 34.23	Fe I 20	0.95	52	34.34
35.39	H 9	10.15	0	
36.09	Ti II 12	0.60	62:	
* 38.29	Mg I 3	2.70	20	38.38
*3840.44	Fe I 20	0.99	53	40.54
41.05	Fe I 45	1.60	57	41.15
43.03	Zr II 7	0.36	86	
* 49.97	Fe I 20	1.01	69	50.08
50.82	Fe I 22	0.99	90	
*3856.37	Fe I 4	0.05	54	56.45
58.30	Ni I 32	0.42	91	
* 59.91	Fe I 4	0.00	28	60.00
* 65.53	Fe I 20	1.01	77	65.63
66.74	V II 11	1.42	93	
*3872.50	Fe I 20	0.99	74	72.60
* 78.02	Fe I 20	0.95	71	78.11
78.58	Fe I 4	0.09	58	78.66
* 82.28	Ti II 34	1.11	87	
* 86.28	Fe I 4	0.05	42	86.37
*3887.05	Fe I 20	0.91	76	
88.52	Fe I 45	1.60	:	
89.05	H 8	10.15	0	
* 95.66	Fe I 4	0.11	74	95.74
98.01	Fe I 20	1.01	92	
*3899.71	Fe I 4	0.09	67	99.78
*3900.55	Ti II 34	1.13	4	00.64
02.95	Fe I 45	1.55	76	03.04
03.27	V II 11	1.47	89:	
05.53	Si I 3	1.90	94	
*3906.48	Fe I 4	0.11	86	
* 13.46	Ti II 34	1.11	14	03.56
14.48	Fe II 3	1.66	91	
16.42	V II 10	1.42	93	
* 20.26	Fe I 4	0.12	65	20.36
*3922.91	Fe I 4	0.05	69	23.02
27.92	Fe I 4	0.11	67	28.01
* 30.30	Fe I 4	0.09	64	30.40
* 32.01	Ti II 34	1.13	73	
33.66	Ca II 1	0.00	0	33.73
3938.29	Fe II 3	1.66	82	38.40
44.01	Al I 1	0.00	80	44.10
45.21	Fe II 3	1.69	92	
50.35	Y II 6	0.10	93	
51.97	V II 10	1.47	86	
3958.24	Zr II 16	0.52	88	
61.52	Al I 1	0.01	67	61.66
68.47	Ca II 1	0.00	0	68.55
69.26	Fe I 43	1.48	63:	
70.07	Hε	10.15	0	
3981.61	Fe II 3	1.72	94:	
82.00	Ti II 11	0.57	87	
82.59	Y II 6	0.13	90	
87.63	Ti II 11	0.60	91	
89.80	V II 32	1.80	95:	
3997.13	V II 9	1.47	94:	
98.98	Zr II 16	0.56	93:	
4005.26	Fe I 43	1.55	76	05.36
05.71	V II 32	1.81	87	
12.37	Ti II 11	0.57	49	12.51
4014.49	Sc II 28	0.31	94:	
23.39	V II 32	1.80	94:	
25.14	Ti II 11	0.60	74	25.26
28.33	Ti II 87	1.88	86	
30.76	Mn I 2	0.00	77	
4033.07	Mn I 2	0.00	79	33.16
34.49	Mn I 2	0.00	90	
35.63	V II 32	1.79	92	
45.82	Fe I 43	1.48	39	45.91
53.81	Ti II 87	1.88	89	
4061.09	Nd II 10	0.47	95:	
63.60	Fe I 43	1.55	50	53.72
67.05	?	4.01	92	
71.74	Fe I 43	1.60	54	71.87
77.71	Sr II 1	0.00	16	77.80
4101.74	Hδ	10.15	0	
49.22	Zr II 41	0.80	92	
61.20	Zr II 42	0.71	95:	
61.52	Ti II 21	1.08	88	
63.64	Ti II 105	2.58	91	
4171.90	Ti II 105	2.59	94	
73.45	Fe II 27	2.57)	56	
73.54	Ti II 21	1.08		
77.54	Y II 14	0.41	85	
78.86	Fe II 28	2.57	61	78.98

λ (Å)	R.M.T.	Lower E.P. (eV)	R_c	λ (Å) (meas.)
4184.33	Ti II 21	1.08	95:	
*4202.03	Fe I 42	1.48	74	02.16
05.05	Eu II 1	0.00	94	
08.99	Zr II 41	0.71	92	
15.52	Sr II 1	0.00	19	15.64
4226.73	Ca I 2	0.00	29	26.82
32.38	Nd II 8 ?	0.06	93:	
33.17	Fe II 27	2.57	20	33.29
46.83	Sc II 7	0.31	13	46.95
* 50.79	Fe I 42	1.55	81	
4254.35	Cr I 1	0.00	42	54.46
58.16	Fe II 28	2.57	93	
* 71.76	Fe I 42	1.48	53	71.87
73.32	Fe II 27	2.69	93	
74.80	Cr I 1	0.00	42	74.91
*4287.89	Ti II 20	1.08	78	
89.72	Cr I 1	0.00	49	89.84
* 90.22	Ti II 41	1.16	39	90.33
94.10	Ti II 20	1.08)	29	
94.13	Fe I 41	1.48		
4296.57	Fe II 28	2.69	81	
*4300.05	Ti II 41	1.18	16	00.15
01.93	Ti II 41	1.16	58	02.07
02.53	Ca I 5	1.89	91	
03.17	Fe II 27	2.69	62	
4303.57	Nd II 10	0.00	88	
* 07.90	Ti II 41	1.18)	30	
07.91	Fe I 42	1.55		
* 12.86	Ti II 41	1.18	51	13.01
14.08	Sc II 15	0.62	58	14.22
*4314.98	Ti II 41	1.16	51	15.10
20.75	Sc II 15	0.60	60	
20.97	Ti II 41	1.16	:	
25.01	Sc II 15	0.59	70	25.13
* 25.77	Fe I 42	1.60	52	25.90
4330.71	Ti II 41	1.18	89:	
* 37.92	Ti II 20	1.08	34	
40.47	Hγ	10.15	0	
* 44.29	Ti II 20	1.08	81	
51.76	Fe II 27	2.69	38	
4358.17	Nd II 10	0.32	93	
67.66	Ti II 104	2.58	92	
69.40	Fe II 28	2.77	94	
74.46	Sc II 14	0.62	75	
74.94	Y II 13	0.41	81	
*4383.55	Fe I 41	1.48	31	83.68
85.38	Fe II 27	2.77	72	
* 94.06	Ti II 51	1.22	88	
95.03	Ti II 19	1.08	6:	95.14
* 99.77	Ti II 51	1.23	64	99.90
4400.36	Sc II 14	0.60	77	
* 04.75	Fe I 41	1.55	54	04.90
* 15.13	Fe I 41	1.60	76	
15.56	Sc II 14	0.59	74	
16.82	Fe II 27	2.77	68	
*4417.72	Ti II 40	1.16	54	17.87
18.34	Ti II 51	1.23	85	
* 43.80	Ti II 19	1.08	19	43.94
* 50.49	Ti II 19	1.08	62	50.60
* 64.46	Ti II 40	1.16	81	
*4468.49	Ti II 31	1.13	22	68.59
89.19	Fe II 37	2.83	85	
91.40	Fe II 37	2.84	76	
*4501.27	Ti II 31	1.11	28	01.41
08.28	Fe II 38	2.84	65:	
4515.34	Fe II 37	2.83	65	
20.23	Fe II 37	2.71	74	
22.63	Fe II 38	2.83	41	22.75
29.47	Ti II 82	1.56	90	
* 33.97	Ti II 50	1.23	22	34.10
4541.52	Fe II 38	2.84	83	
49.47	Fe II 38	2.82)	9:	
49.62	Ti II 82	1.58		
* 54.03	Ba II 1	0.00	80	
55.89	Fe II 37	2.82	54	56.01
*4563.76	Ti II 50	1.22	39	63.90
* 71.97	Ti II 82	1.56	28	72.10
76.33	Fe II 38	2.83	86	
83.83	Fe II 38	2.79	20	83.98
89.96	Ti II 50	1.23	81	
4629.34	Fe II 37	2.79	53	

by Hardorp et al. is virtually identical to ours. The period is of course established much more accurately from eclipse timings than from radial velocities.

5.2. Masses, luminosities and spectral types of the components

5.2.1. Derivation of the mass ratio

The mass ratio for the two components of a spectroscopic binary system can in principle be derived from their mutual difference in radial velocity, given the orbit of the primary star. In the case of ζ Aur any attempt to measure the B-star lines in the composite spectrum faces uncertainties arising both from the presence of superimposed, sharp but blended, K-star lines, and also from the great intrinsic breadth and low contrast of the B-star lines. The heroic attempt by Tremblot (1934), which was claimed (probably justifiably) to be the first such determination of the masses of spectroscopic binary components in systems that included a K or M-type giant, yielded a mass ratio of 1.88 and individual masses $M_1=16.0\,M_\odot$ and $M_2=8.5\,M_\odot$. Similar dynamical solutions by Lee and Wright (1960) and by Popper (1961) gave mass ratios of 1.2 and 1.48, respectively, and led to Wright's (1970) recommendation of $M_1=8.0\,M_\odot$, $M_2=5.8\,\mathrm{M}_\odot$. However, plausible as those values seemed for the respective component stars, they could not be reconciled with the theoretical masses derived from the radius, effective temperature and luminosity of either star, the theory tending to yield higher masses [e.g. $M_1=22.0\,M_\odot$, $M_2=10.2\,M_\odot$ (Wellmann, 1951)]. A major difficulty lay in assigning a value to the radius of the B star, because the effects of chromospheric extinction prevented a precise timing of the length of partial eclipse or a unique interpretation of second or third contact.

Since the wavelength scales of our spectra of ζ Aur B are in the rest frame of ζ Aur A, and the velocity at any given time of ζ Aur A, relative to the γ-velocity of the system, is known from the radial-velocity orbit, a single measurement of the radial-velocity displacement of the spectrum of ζ Aur B from that of ζ Aur A is all that is required in principle to determine the mass ratio of the component stars. Such a measurement would best be made when the stars are near maximum difference in radial velocity, a condition which unfortunately none of our spectrograms fulfils.

We routinely determine the wavelength displacement of a spectrum by cross-correlation, in which the information from all spectral features is fed simultaneously into one measurement. In the case of a sharp-lined star such as HR 6902 B the relatively wide Balmer lines are not used in the cross-correlation. However, the spectrum of ζ Aur B shows nothing useful for radial-velocity purposes besides Balmer lines and weak He I lines, all broadened by a rotation of some 200 $\mathrm{km\,s^{-1}}$. Any measurement of line positions by whatever method is therefore doomed by the nature of the spectrum to be somewhat uncertain. The cross-correlation method is sensitive to the gradient of the wings of the absorption features being measured, so – especially in applying it to Balmer lines – it is important to use a standard spectrum whose Balmer-line profiles are a close match to those in ζ Aur B. We therefore cross-correlated with one another the two different spectra of ζ Aur B which had been derived from Ce 24156 and S 3985 at phases .54 and .23, respectively. Because both spectra had been generated by subtractions which employed the same spectrum of ζ Aur A, a narrow auto-correlation spike could be expected at zero velocity displacement. Various constraints of the procedure limited the useful spectral range to $\lambda\lambda$3760–4050 Å.

By this method the radial-velocity shift between the two spectra of ζ Aur B was found to be 43 ± 3 km $\mathrm{s^{-1}}$; during that phase interval the K-star velocity (according to the known orbit) had altered by 18.7 km $\mathrm{s^{-1}}$, so the corresponding mass ratio (q) is 1.3, with extreme values of 1.15 and 1.45. However, although these results seem quite definitive in the wavelength region selected, it must be emphasized that the method, as applied here, is very sensitive to peculiarities in the profiles of those few spectral lines used in the measurement. An inherent slope in the continuum, for example, can alter the symmetry of the cross-correlation function, and affect the location of its true centre. There is also some doubt as to whether the spectrum of the K star is the same at all phases; we notice in particular that our spectrogram taken at phase .23 shows the λ3905 Å Si I emission line first noticed more than 50 years ago by Christie and Wilson (1935).

According to the above mass function and mass ratio, the masses of the components are $M_1=7.0\,M_\odot$, $M_2=5.4\,M_\odot$ but with an uncertainty of up to 20% in either value. These figures are very comparable with those derived by Popper (1961), but their accuracy can be significantly improved if we are able to obtain data in the future at the critical epoch in the orbit.

5.2.2. Luminosities and spectral types

The properties of the two component stars have been derived by many authors from photometry made both inside and outside eclipse; representative values are given in Table 3. Given the colours of the K supergiant alone and the magnitude changes in different colours during minima, one can model the observed colours of the composite system in terms of standard stars. Wellmann's careful classification (1951) of K4 II + B7 V, which he derived from eclipse spectra together with a consideration of the confluence of the Balmer series as seen on tracings from composite spectrograms, has been generally accepted and only slight modifications have been offered: Bahng (1958), for example, derived K4 II + B8 V from photoelectric photometry, Lee and Wright (1960) found K3 Ib–II + B6.5 V (the only case in which the spectrum of the B star was actually isolated so that the strengths of H and He lines could be measured unambiguously), Koch et al. (1970) listed K4 Ib + B6.5 V and Burnashev (1983) gave K4 Ib–II + B5 V. A comparison with the results of visual, qualitative

Table 3. Photometry of ζ Aurigae

Star	V	B	U	$(B-V)$	$(U-B)$	Source
A+B	3.75	4.97	5.35	1.22	0.38	Hoffleit (1982)
A	3.89	5.51	7.32	1.62	1.81	Mohin et al. (1980)
B	6.02	5.98	5.54	−0.04	−0.44	=(A+B) minus A

classification, e.g. K0+B1 (Cannon and Pickering, 1918) and G5+B8 (Hill et al., 1975) exemplifies the difficulties of attempting to classify one spectrum in the presence of another of very different colour and type.

We have made our own comparison of the secondary spectrum (Fig. 3) with that of B5 V and B7 V stars, and concluded that its type is B6.5; we have not got sufficient comparison spectra of high-luminosity K stars to define the spectral type of the giant.

Further information about the spectral types and relative luminosities may be gained from measurements of the fluxes that are attributed to the component spectra during the subtraction procedure. The flux ratios determined for the two components of ζ Aur seen outside eclipse were compared with similar ratios derived from Willstrop's (1965) measurements for suitable pairs of standard stars; the results were in agreement with those mentioned above, but again the lack of an adequate range of standard stars of either type meant that the ratios derived from Willstrop's flux measurements were sensitive to any idiosyncrasies in the particular spectra measured.

Tests on the purely composite spectrum (Ce 24156) indicated a preference for γ Phe (K5 II) as the best match for the supergiant among Willstrop's sample, and a hybrid B5 V (an average of σ Sgr and κ Cen (B2 V) and ϕ Eri and η Aqr (B8 V)) to represent the companion. To give the observed B/K ratios, Willstrop's absolute fluxes needed to be scaled by a factor, representing the difference in magnitude between the components, of $\Delta M_V = 2.2$. Had a K star of somewhat higher luminosity, as more fitting to ζ Aur A, been available, the derived magnitude difference would have been greater. Our result is also rather sensitive to the exact fraction of eclipse spectrum used in the subtraction procedure. The absolute visual magnitudes of the B and K components calculated by Erhorn (1990) are $-1\overset{m}{.}05$ and $-3\overset{m}{.}8$, respectively, i.e. $\Delta M_V = 2.75$, and correspond closely to B6.5 IV–V and K4 Ib–II in the tabulation by Schmidt-Kaler (1982) of M_V versus spectral type.

5.3. Geometry of the eclipse

By multiplying the relative transverse velocity of the two stars by the duration of the eclipse, we can determine the length of the chord traversed by the B star behind its supergiant companion. A comparison of the eclipse chord with the radius of the supergiant gives the latitude of the chord. We are then in a position to try to establish the relative positions of the stars at the times of our observations.

The relative tangential velocity of the stars at the time of eclipse is $(1+q)$ times the tangential velocity of the primary star, which is found from the orbital elements to be 28.5 km s^{-1} at conjunction (approximately mid-eclipse). With $q=1.3$ (Sect. 5.2.1) the relative tangential velocity is 65.5 km s^{-1}. Since primary conjuction takes place shortly (about 69 days) before periastron the orbital velocities of the component stars are increasing during totality, but owing to the orientation of the orbit to the line of sight ($\omega = 329°$) only the *radial* velocity of either star appears to be increasing; the relative *tangential* velocity reaches a maximum soon after mid-eclipse and is a little less (about 1.5 km s^{-1}) during ingress and egress. We have adopted a mean value of 65 km s^{-1} to represent the relative tangential velocity throughout totality because the inaccuracy of the various relevant data does not warrant a more rigorous approach.

For the duration of total eclipse we adopt a value of 36.8 days, which is representative of the remarkably accordant estimates given by Oosterhoff (1935), Christie (1940), Roach (1941) and Pettit (1948). Tanabe and Nakamura (1957) and Hardorp et al. (1966) suggested the possibility of a secular increase in this quantity, but the evidence is not conclusive. Taken in conjunction with the transverse velocity given above, a duration of $36\overset{d}{.}8$ leads to an eclipse chord of half-length 148 $R_\odot$. Erhorn's (1990) careful modelling of the photometry of the ζ Aur system has given the radii of the components as $R_K = 166\ R_\odot$ and $R_B = 5.1\ R_\odot$ (with an uncertainty of 5 to 10%), in very good agreement with Ferluga's (1990) speckle interferometry. The eclipse is only total while the projected distance between the centres of the two stars is less than the difference of their radii. Thus the latitude ϕ (on the supergiant) of the eclipse is $\cos^{-1}$ [(eclipse semi-chord)/(difference in radii)], viz. about 23°. However, the uncertainties associated with the eclipse chord (chiefly through the mass ratio) and the stellar radii are such as to admit latitudes ranging all the way from the equator to about $\pm 40°$.

The partial phase of the eclipse lasts while the B star moves through a projected distance $2R_B \sec\phi$ with respect to the limb of the supergiant. The duration of the partial phase, according to the parameters we have adopted for R_B, ϕ and the relative velocity (64 km s^{-1}) at ingress, is $1\overset{d}{.}4 \pm 0\overset{d}{.}2$, the error limits deriving from those in R_B and ϕ.

The duration of partial eclipse can in principle be measured with much greater accuracy from photometry. However, Grant and Abt's (1959) ingress photometry depicts the difficulty of assigning exact times to the contacts of a bodily eclipse when chromospheric absorption is present. Doubts about the relative importance of chromospheric extinction and geometrical eclipse plagued the early interpreters – for example, Menzel (1936) suggested the situation to be like that of "a planet setting in a smoky atmosphere, disappearing before it reaches the horizon".

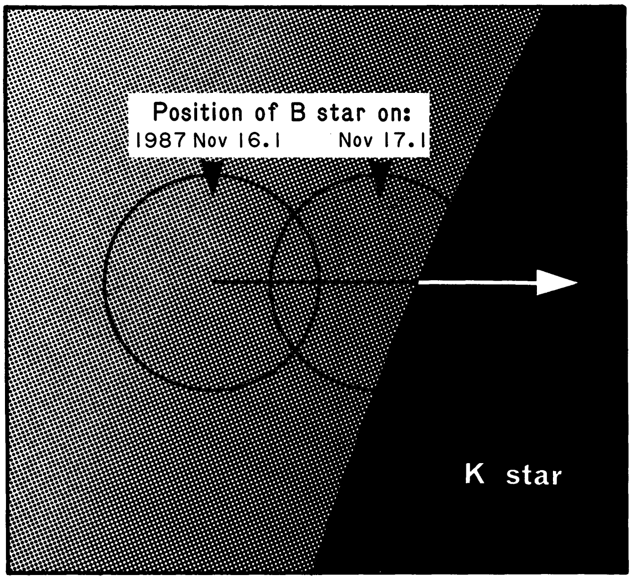

Fig. 7. Geometry of the eclipse of ζ Aur at ingress. The diagram shows, to scale, the path of ζ Aur B behind the limb of the supergiant and the relative positions of the two stars on 1987 Nov. 16.1 and Nov. 17.1. According to our model the eclipse occurs at a latitude of about $\pm 23°$ on the supergiant; however, the associated uncertainties are such that a latitude anywhere between 0° and $\pm 40°$ cannot be excluded

The values of $1\overset{d}{.}45$ given by Oosterhoff (1935), $1\overset{d}{.}35$ by Christie (1940), $1\overset{d}{.}3$ by Roach (1941) and $1\overset{d}{.}35$ by Pettit (1948) may be compared with the $1\overset{d}{.}5$ adopted by later authors such as Larsson-Leander (1961), Hardorp et al. (1966) and Wright (1970).

We have tried to assess from our spectrophotometry the progress of the eclipse between Nov. 16.1 and Nov. 17.1. Implicit in our spectral subtraction method is the quantitative division of the observed flux (Sect. 5.2) between the K supergiant and the B star. Comparison of that ratio, after correction of the B-star flux for absorption due to chromospheric lines, with the out-of-eclipse value at the corresponding wavelength indicates the proportion of the B-star continuum remaining on each night. We can thus confirm that the eclipse was only chromospheric on Nov. 16.1, but that by Nov. 16.9 the B star was approximately 25% eclipsed, and about 40% eclipsed by Nov. 17.1. The partial-eclipse estimates, which are sensitive to the subtraction procedure, were derived from the spectral region shortward of λ4000 Å, where a chromospheric spectrum could definitely be distinguished (see Fig. 6 and the comment about it at the end of Sect. 4.1); at longer wavelengths the uncertainty surrounding the recovery of the chromospheric spectrum renders the corresponding flux measurements unreliable. Our best estimates for the dates of first and second contacts are Nov. 16.6 and Nov. 18.0 respectively. In Fig. 7 we present a scale diagram of the position of the B star relative to the limb of the supergiant on the two nights in question; those positions are fundamental to Paper 2.

5.4. *Radial velocity of the chromosphere*

The spectra in Fig. 5 are presented in the rest frame of the K star, so the line positions in Table 2 immediately furnish a value for the radial velocity of the chromosphere relative to the photosphere of the primary. On Nov. 16.1 the radial velocity derived from 51 suitable-looking lines of H I, Mg I, Sc II, Ti II, Cr I and Fe II lines was 8.5 ± 0.14 km s^{-1} (standard error of the mean). Lines of Fe I having $\lambda > 4000$ Å gave the same result, but the value derived from Fe I lines having $\lambda < 4000$ Å was less, significantly so for $\lambda <$ 3800 Å (6.7 ± 0.3 km s^{-1}). The cause of such individualistic behaviour of those Fe I lines probably lies with the subtraction procedure. Most of the chromospheric features are stronger than their counterparts in the photospheric spectrum, whereas the reverse is true for Fe I lines, which are so intense in the photospheric spectrum that accurate spectrophotometry of their cores is hard to attain; the problem has been compounded by the weakness of both chromospheric exposures, and particularly of the total-eclipse exposure, at short wavelengths. Since the photospheric contribution to the composite + chromospheric spectrum lies on the short-wavelength side of the chromospheric features, incorrect subtraction of it may affect the position of the centroid of the residual line; tests showed that an uncovered chromospheric line suffered a significant negative wavelength shift (about 0.02 Å or 1.5 km s^{-1}), if the amount of subtracted photospheric spectrum were reduced from, say, 55% to 50%. Uncertainties in the spectrophotometry near to the lower intensity limit of the photographic plate could account for such errors in the cores of strong lines in the short-wavelength region.

Our 51 lines do not include the Ca II H and K lines, which were the features normally used by others in determining the motion of the chromosphere. As Fig. 5 shows, the H and K lines are both saturated, making it impossible to know where the true line centre is.

It has frequently been reported that the chromosphere of a ζ Aur-type supergiant does not appear to rotate rigidly with the star but to possess independent motions which are not necessarily repeated from one eclipse to another. Wavelength shifts in the Ca II K-line were originally interpreted in terms of rotation of the K-supergiant primary (Guthnick and Schneller, 1932). However, differences in the behaviour of those K-line strengths at the next eclipse prompted Beer (1934) to suggest that the Ca II atmosphere surrounding ζ Aur alters in shape or size with time, an important conclusion that has been reiterated by Christie (1938b), Beer (1940), Welsh (1949), Beer and Ovenden (1951), Wilson and Abt (1954), Faraggiana (1965) and Kawabata and Saito (1975) as more eclipse data have become available. Even more compelling, in this context, is the detailed study of chromospheric velocities in 31 Cyg (McLaughlin, 1952). Those investigations, however, related to regions of the chromosphere that extend for many B-star diameters above the photosphere, whereas ours is limited to observations when the line of sight to the nearer limb of the B star passed less than one B-star radius above the photosphere; we therefore feel justified in attempting to interpret the chromospheric-line velocities in terms of rigid rotation.

On Nov. 16.1 the projected distance of the centre of the B star from the axis of rotation of the K star was about 163 $R_\odot$. The velocity, at that radius, of 8.5 km s^{-1} represents a rotational period for the K star of 1000 days – not significantly different from the orbital period of 972 days, and the similarity suggests synchronous rotation. On Nov. 17.1 the radial velocity, derived (with much poorer accuracy) from 8 chromospheric Balmer lines, of 8.5 ± 0.8 km s^{-1}, helps to confirm that rotation period. In this connection it is of interest that the only radial-velocity spectrometer trace from which we have yet been able to derive a value for the rotational velocity yields a value of 9.5 km s^{-1} for $v\sin i$ (on the assumption that the whole of the line-broadening arises from rotation), corresponding to a rotation period of about 890 days. According to Hut (1981) the spin–orbit coupling should eventually lead to a "pseudo-synchronization" period that is smaller than the orbital period by a factor of 2.08 (computed from the orbital eccentricity, $e = 0.406$), i.e. 407 days. If Hut's discussion is indeed relevant to ζ Aur, the similarity between the orbital period and the rotation period suggested both by the displacement of the chromospheric spectrum and by the broadening of the photospheric lines must be dismissed as a mere coincidence; but, if so, it is a very striking one.

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