21. THE CHROMOSPHERIC SPECTRUM AND THE ATMOSPHERE OF 31 CYGNI

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The binary 31 Cygni is not, in the ordinary sense, an unstable star. Nevertheless, the organizers of this symposium have invited the present paper as a discussion of additional recent evidence of random motions of masses of gas in the atmospheres of the late-type giant components of certain double stars.

31 Cygni is an eclipsing binary similar in general nature to the well-known system, ζ Aurigae. It consists of a super-giant K-type primary and a secondary of type B 5 or possibly a little earlier, according to Wright and Lee. The two stars are equally bright near λ 3900. While 31 Cygni has long been known as a spectroscopic binary, its eclipsing nature was predicted by D. B. McLaughlin only about five years ago from an examination of spectrograms taken in 1941. The period is about 3800 days. The only well-observed eclipse occurred in 1951 when series of spectrograms were obtained at Victoria, Ann Arbor and Stockholm, and some fragmentary photo-electric observations were made.

Publications on 31 Cygni may be grouped into earlier investigations of the spectrum, radial velocities, and orbits [1-4], the suggestion that the star was an eclipsing binary [5], the photo-electric observations [6], and papers describing results obtained from the Ann Arbor [7, 8], Stockholm [9] and Victoria [10-13] spectrograms of 1951. The material given in the present discussion is taken from the three papers: (*a*) reference [10] above; (*b*) a paper being prepared by R. M. Petrie and A. McKellar on the Victoria observations of 31 Cygni; and (*c*) a paper being prepared by A. McKellar, L. H. Aller, G. J. Odgers, and E. H. Richardson on the chromospheric K-line of Ca II in the spectrum of 31 Cygni. The latter two papers are to appear as *Publications of the Dominion Astrophysical Observatory*, vol. XI, Nos. 1 and 2.

In 1951 spectroscopic effects of the impending eclipse of 31 Cygni were observed as early as 1 June. The chromospheric lines increased in intensity, slowly at first but rapidly in early August during the final days of ingress. Total eclipse of the comparatively small B-type star began on 12 August

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and lasted until 12 October. During egress, the spectroscopic phenomena of atmospheric eclipse occurred in the reverse order and were detectable until the end of the year. Combination of the existing orbital and photometric data gives the minimum diameter of the K-type super-giant component as 150⊙ and the diameter of the B-type star as about 5⊙. It may be remarked that our preliminary measurements on the secondary spectrum indicate a somewhat larger mass ratio than has been given and so would require larger minimum sizes for the stars.

Most of the spectrograms photographed at Victoria were obtained with the third order of a 15,000-lines-per-inch grating and a collimator-camera lens of 45 inches focal length in a Littrow mounting, giving the comparatively high dispersion of 4·6 Å/mm. The wave-length region covered was from λ 3700 to λ 4600 except for a gap from λ 4100 to λ 4200.

Study and interpretation of the spectrograms has shown, in at least three ways, evidence of structure and motions in the outer atmosphere of the super-giant star. The three will be briefly described. Fuller details may be read in the papers cited above. The term 'chromospheric' as used above and throughout this paper refers to the extra absorptions present in the composite spectrum due to the light from the early-type star traversing the atmosphere of the late-type super-giant for periods before and after total eclipse. While it is not implied that the outer atmosphere of the primary component is similar to the solar chromosphere, the term has seemed apt since, except for scale, certain similarities do exist.

(1) STRUCTURE AND MOTIONS IN THE OUTER CHROMOSPHERE DEDUCED FROM COMPLEX K LINES

The chromospheric K line of Ca II during egress in late October and in November and December 1951, showed definite structure. From 26–31 October, the principal wide chromospheric line was accompanied by a weaker wing or satellite which, with respect to the rectangular-shaped principal line, occupied positions corresponding to radial-velocity shifts as great as 130 km./sec. Also, at various times from mid-November until late December, the K line was often double, the components varying in intensity and separation from day to day and week to week. The separation in wave-length corresponded to radial-velocity differences of 22–44 km./sec.

These observations have already been described [10] and have been interpreted as evidence of the existence of discrete moving clouds of material in the outer chromosphere of the K-type giant star.

The reproductions in Fig. 1 show spectrograms in the region λ 3878 to λ 3980 for the period 31 July to 10 August 1951, just preceding totality, as well as a spectrogram in totality and one almost a year later.

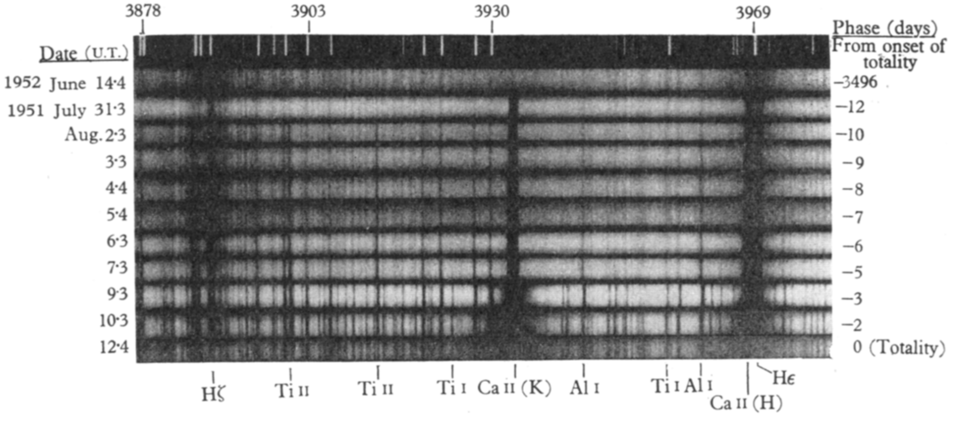

Fig. 1. Chromospheric spectrum λ 3878–λ 3980, late stage of ingress, 1951.

(2) THE 'TURBULENT' VELOCITY INDICATED BY THE PROFILES OF THE CHROMOSPHERIC K LINE

Intensity profiles have been derived for the chromospheric K line from the Victoria plates covering ingress and egress and from the Ann Arbor plates obtained during egress. These line profiles have been compared with calculated profiles.

As shown by examples given in Fig. 2 reasonably good accord between observed and calculated profiles is secured using values of turbulent velocity ranging from 20 km./sec. for the low chromosphere to 10 km./sec. for the masses of material in the high chromosphere. It may be remarked that Miss Underhill [11] found the widths of the four Fe I chromospheric lines she studied, which originated in the lower atmosphere of the K-type star, to correspond to motions up to 20 km./sec.

When the equivalent widths of the K line are plotted against the line depths (corrected for instrumental effects), as shown in Fig. 3, we obtain further evidence of motion among the Ca II atoms in the outer chromosphere of the giant star. On some days the K line shows no structure, and its shape corresponds to a calculated profile for a v_T of about 10 km./sec. However, on other days both before and after eclipse the line is not actually double, but shows some indication of unresolved structure, such as a lack of symmetry. Then the relation between equivalent width and depth, as shown by the triangular symbols grouped toward the right side of Fig. 3,

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indicates values of turbulent velocity of 20 km./sec. or more. In these cases the larger velocities presumably arise from absorption in two or more masses of gas having different velocity distributions in the line of sight. The line of sight is, of course, tangential to the stellar surface. The relative

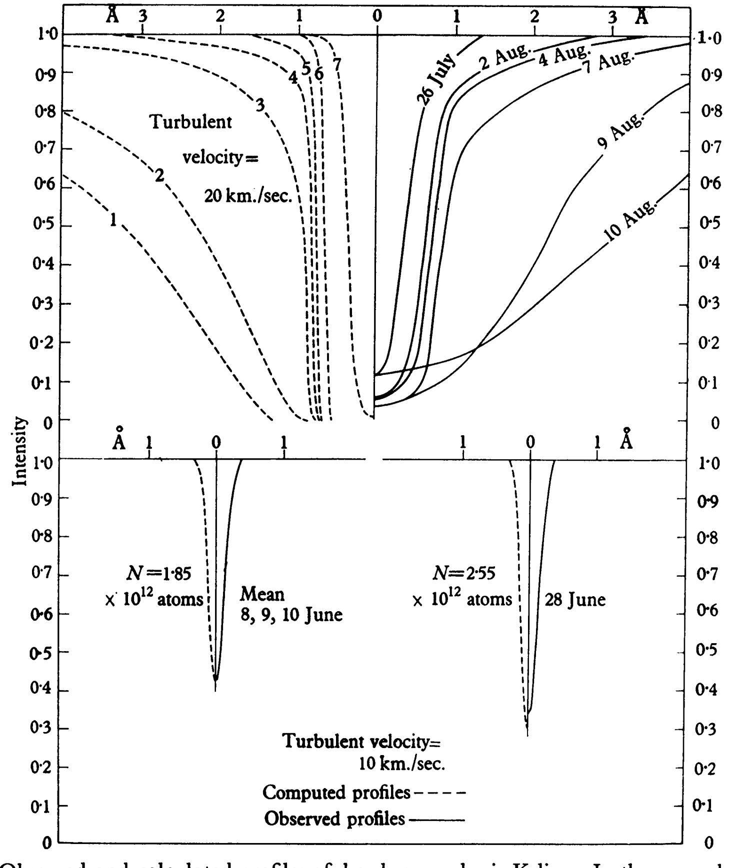

Fig. 2. Observed and calculated profiles of the chromospheric K line. In the upper half of this figure the relation of the profile number to the number of atoms is as follows: 1, 355×10^{16}; 2, 177×10^{16}; 3, 22×10^{16}; 4, $5{\cdot}8\times10^{16}$; 5, $1{\cdot}9\times10^{16}$; 6, $0{\cdot}18\times10^{16}$; 7, $0{\cdot}002\times10^{16}$.

velocities of the components are sufficient to widen the line but not to produce definite multiplicity.

(3) RADIAL-VELOCITY MEASUREMENTS ON THE CHROMOSPHERIC LINES

The most recently completed section of the work on the spectrum of 31 Cygni is the measurement, for radial velocity, of the chromospheric lines in the spectrum from twelve days before total eclipse until onset of totality and from the end of totality for a period of fourteen days. The coverage during ingress is fairly complete, but during egress it is fragmentary.

The plates measured were all third-order grating plates (4·6 Å/mm.) except those of 16 October, for which date three prismatic spectrograms of

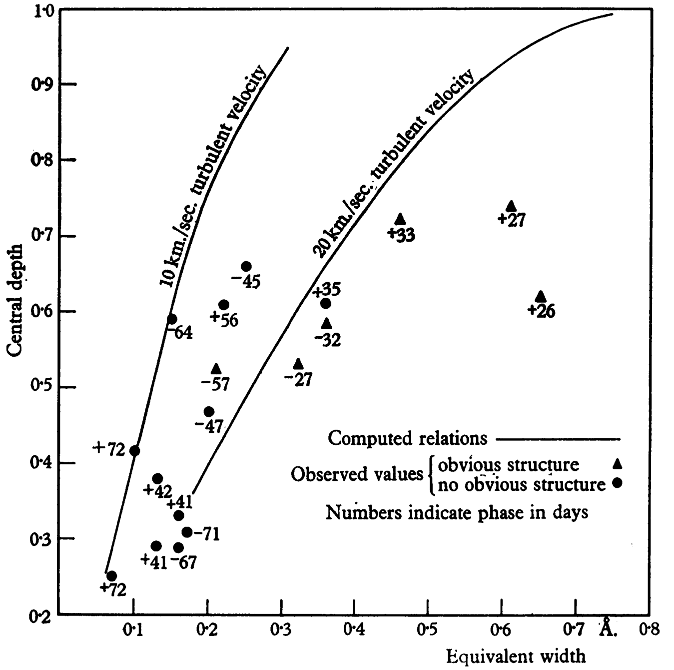

Fig. 3. Relationship between the central depth and the equivalent width of the chromospheric K line.

lower dispersion, 20 Å/mm. at λ 3933, were available. For the grating plates, measurements on the spectrum of α Persei indicate the probable error of the velocity from a single line of average weight to be $\pm$ 3 km./sec.

Only lines clearly chromospheric in character were measured. Lines known or suspected to be blended were omitted. The Balmer lines of hydrogen were surprisingly badly affected by blending. The numbers and origin of chromospheric lines measured (those which survived the inspection for blending and chromospheric character) are shown in the following tabulation:

Atom	Fe I	Ti I	Ti II	Mn I	Cr I	Ni I	Al I	Mg I	Ca II	Sr II	Sc II	V I	Y I	Ba II	Ca I
No. of Lines	46	10	7	3	4	3	2	3	2	2	2	1	1	1	1

The results of the measurements are shown graphically in Fig. 4. The time scale used for the period of total eclipse is only one-third that used in the rest of the figure. The most reliable results, those of Fe I, Ti I and Ti II, are shown at the top, the next most reliable group is in the middle, and the least reliable at the bottom of the figure. For each group the segment of the radial-velocity curve of the orbital motion of the K-type star is given. This radial-velocity curve, as redetermined at Victoria, agrees exactly in slope with those of McLaughlin [8] and of Miss Vinter Hansen [4], and is within 0·26 km./sec. of their values at mid-eclipse.

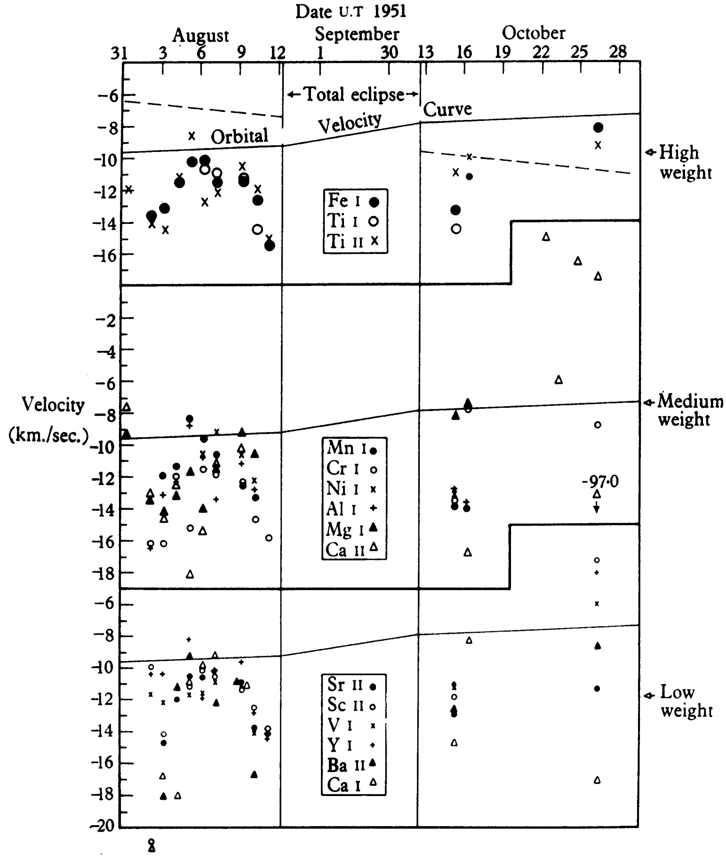

Fig. 4. The radial velocity of 31 Cygni in the vicinity of eclipse from chromospheric lines.

It is apparent that the radial velocities measured for the chromospheric lines fall systematically below the orbital curve, both before and after eclipse, by several km./sec. The effect as shown by the most reliable group is surprisingly well duplicated by the other two groups. Since the orbital velocity curve was determined from similar spectrograms during totality and at phases far removed from totality and since, also, the grating spectrograms gave the accepted velocity for the standard velocity star α Persei, this discrepancy is considered to be an actual velocity effect. Furthermore, in their general behaviour, our measurements agree with those of McLaughlin [8] over the same time interval.

The deviations of the velocities from the orbital curve do not correspond to simple stellar rotation. For rotation, the deviations would be of opposite sign before and after totality, which is not the case. For rotation in the same sense as orbital motion, the deviation at ingress would be positive, not negative as observed. In the top section of Fig. 4, the broken lines show the minimum rotational-velocity effect, assuming equal rotational and orbital periods and similar directions of motion.

We are inclined to attribute the deviations in velocity to tangential components of atmospheric motions, possibly random or possibly partly systematic. The source or driving force of the motions cannot at present be specified, but since the gravitational acceleration at the surface of the super-giant star is unlikely to exceed 10 cm./sec.^{2}, and the atmosphere has a very low mean density, irregular horizontal drift motions could be easily initiated and would not be quickly damped out. Tidal forces are much too small to be an important factor in the problem. Velocity differences between chromospheric and stellar lines, similar to those just described for 31 Cygni, have long been known for ζ Aurigae. It will be interesting and important to examine whether deviations in velocity of chromospheric lines near the 1961–2 eclipse of 31 Cygni will be similar in sign and magnitude to those found for the 1951 eclipse. If so, some systematic source can be sought; if not, the motions are presumably random.

We are left with the following picture of the atmosphere of the super-giant K-type star. The inner chromosphere observed for about twelve days before or after totality, and extending approximately one-fifth of a diameter above the main body of the star, shows evidence of motions with velocities of the order of 20 km./sec. from K line profiles, and of components of motion up to several km./sec., given by radial-velocity deviations of chromospheric lines from the orbital radial-velocity curve. Evidence of occasional high-speed outbursts of gas from the lower chromosphere is given by the satellite lines of the chromospheric K line (26 October to November 1951), that show displacements corresponding to as much as 130 km./sec. The measured motion is the component tangential to the stellar surface. Finally, in the outer atmosphere there must be discrete clouds of gaseous material having, on present evidence of double chromospheric K lines, relative velocities up to 40 km./sec. in the line of sight.

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[14] See, for example, A. McKellar and R. M. Petrie, *M.N.* **114**, 641 (1952); *Contr. Dom. Astrophys. Obs.* No. 29, where references to earlier work on the spectrum of ζ Aurigae are given.