OBSERVATIONS OF ζ AURIGAE STARS AND THEIR INTERPRETATION

by

H. G. Groth

Universitäts-Sternwarte Munchen
Institut für Astronomie und Astrophysik

ABSTRACT

A summary of information on the extended atmosphere of the K component coming from three eclipsing binaries consisting of a K supergiant and a main sequence B star. Various anomalies exist: (1) Discrepancy between electron density and metallic density inferred from observations, noting that the electrons should come from the metals. This suggests a cloud structure in the atmosphere. (2) Anomalous excitation temperatures and populations of the second quantum level of hydrogen suggests a solar-chromosphere type behavior for these K atmospheres. (3) Significant changes in the profiles of the Ca^+ lines from one eclipse to another. The necessity to distinguish between effects coming from radiation of the B star on the K atmosphere and chromospheric-like effects is emphasized.

Key words: chromosphere, super-excitation, Russell-Adams effect, chromospheric clouds.

It is very difficult to get direct information about the outermost layers of stars other than the sun. The information comes mainly from spectral pecularities and the absorption or emission in the centers of strong lines. But there is a group of stars that permits us to make detailed analysis of the extended outer atmospheres of a few late type supergiants. These are the eclipsing and spectroscopic binaries with long period (972^d - 3800^d). I shall discuss three of them: ζ Aur, 31 Cyg, and

32 Cyg. Each system consists of a K type supergiant (K3 - K5 Ib) and a main sequence B star (B3-B8 V). The diameter of the B type component is small compared with the dimensions of the extended atmospheres of the K supergiants. Both components show equal intensity near λ 4000, so that outside eclipse the spectrum is the sum of a K and a B type spectrum. Some time before or after the total eclipse of the B star by the K star, the light of the B star is absorbed in the chromosphere (the outer layers of the atmosphere) of the K supergiant. These additional absorption lines have been observed and analysed by several authors at different heights above the "limb" of the star, giving valuable information of the physical state of these layers (see, i.e., O. C. Wilson 1960).

But in spite of a long series of observational results and great effort in the analysis of the observations in the last thirty years, there is no satisfactory interpretation.

At a first glance the problem seems to be quite simple. There is a light source and some absorbing material, a nearly ideal situation for spectroscopic analysis. But unfortunately a B star is a very hot light source and the separation of the two components is not very large. For ζ Aur the mean separation of the K star and the B star is only three times the radius of the K component. As a consequence we must expect an influence of the B radiation on the K atmosphere, and so we get into trouble.

What information can we get from the observations? If we measure the chromospheric part of the absorption, we can derive the number of atoms and its gradient for different elements in a column across the chromosphere by using the curve-of-growth method for pure absorption. By assuming spherical symmetry it is easy to calculate the number density from the solution of an Abel-type integral equation. If the assumption of spherical symmetry is correct, we have the number of atoms per cm^3 and its dependence on height, that is on the distance from the limb of the K star, for some atoms: Hydrogen (Balmer quanta), Ca II, Ca I, (Fe II), Fe I, Ti II, Ti I, and others. From the curve-of-growth analysis we have in addition excitation temperatures, which are of the order of 4000 to 4500°K. Some authors have deduced an increasing temperature with increasing height. The microturbulence comes out to be 10-20 km/sec.

If we employ normal abundance ratios of the metals to hydrogen, we get a total hydrogen density of 10^{10} atoms/cm^3 at a height of 4×10^6 km above the limb for ζ Aur. The decrease of density can be described by an exponential law.

$$N = N_o \cdot e^{-\alpha h}$$

with α of the order of a few times 10^{-7}km^{-1}.

All authors agree (for all three stars) that the radiation of the B star is not able to ionize hydrogen in the K chromosphere. Some detailed calculations by Mr. Pöllitsch of our Institute have shown for the system ζ Aur that the Strömgren limit would be in the atmosphere of the B component. We should expect to have only neutral hydrogen in the K type atmosphere and as a consequence all electrons would come from the metals. In the case of the first ionisation of the metals (5-8 eV) we can neglect the optical dilution and take only pure geometrical dilution of the B radiation (the dilution factor is of the order of 10^{-6} to 10^{-7}). We can use a modified Saha equation and calculate the electron density assuming an appropriate temperature for the B star. We find that the local temperature calculated from the diluted B radiation is approximately the same as the excitation temperature derived by the curve-of-growth method. pg 188 [illegible]

Using the Saha equation for the metallic ionisation, we are surprised to find a very large electron density of 10^9-10^{10} per cm^3, the number of metallic atoms being of the order of 10^6 per cm^3. With the hydrogen completely neutral we must come to the conclusion that the material in the chromosphere of the K star must be concentrated in clouds that have a density 10^3-10^4 times larger than we calculated for a smooth density distribution. The number of clouds in the line of sight must be large enough to produce rather small density fluctuations. There are observations that show some fluctuations especially in the K line of Ca II. It seems that we can explain the ionisation of metals by the radiation of the B star, if we propose a cloudy structure for the K atmosphere. In this connection, there is only a problem with the second ionisation of calcium which has an ionisation potential of 11.8 eV. A larger number of Ca III atoms could be formed than has been considered, but this is of minor importance here.

The main question and, in my opinion, the key for the whole problem is the excitation of the Balmer lines.

From the observed number of metallic atoms, assuming normal abundances, we get the total number of hydrogen atoms. We observe the Balmer lines in absorption and get the number of atoms in the second state. Using the normal Boltzmann equation, we find in any case a temperature of 6000-7000°K for the excitation of hydrogen, which is considerably higher than the excitation temperature of the metals. The Lyα radiation is responsible for the population of the second state of hydrogen. To get enough Lyα quanta for the observed Balmer lines we have to consider several possibilities:

1. Direct Lyα radiation from the B star.
   a. If the Lyα line is an absorption feature, the number of Lyα quanta is too small unless the star has a temperature of the order of 100,000°K.
   b. If Lyα shows up in emission, there could be enough quanta coming from the B star itself, but we do not know how strong the Lyα radiation of a main sequence B star can be.
2. Lyα quanta coming from the H II zone around the B star. It is very difficult to calculate the Lyα radiation field in this geometrically very complicated case. If the H II zone ends up in the B atmosphere we have case 1b.
3. Increase of temperature in the K chromosphere, that means a transition from chromosphere to corona as in the case of the sun.

The most favourable possibilities are cases 2 and 3. If we have an H II zone around the B star, there would be a transfer of Ly continuum radiation to Lyα radiation in a manner similar to the cascade processes which occur in diffuse nebulae. Any Ly continuum quantum can end up as a Lyα quantum, so these quanta can be available in a considerable number for the excitation of the second state in the chromosphere.

But when considering this process we must remember:

1. the ionisation is going on during the whole orbital period.
2. long wavelength quanta are also produced which should be observed as emission components in the Balmer lines, especially Hα.

In this connection it is important to mention that the orbits of all stars are very eccentric. For ζ Aur the eccentricity is 0.4. If there was a considerable amount of emission from the H II zone around the B star, this emission should show a periodic change, because the density of the material must change with the orbital period. It would be very interesting to observe Hα and other Balmer lines during the whole orbital period and to look for intensity fluctuations with this period. The amplitude of these intensity changes may be very small, so that I am not quite sure whether the changes would be observable or not.

As mentioned earlier, the high excitation of the second state of hydrogen could be produced in the K chromosphere itself. Wellmann and I tried to calculate this effect which we called "superexcitation," in the case of ζ Aur (P. Wellmann 1939; H. G. Groth 1957). The result was that there must be an increase of temperature with increasing excitation or ionisation potential. For hydrogen excitation and ionisation we found a temperature of approximately 6000°K. The chromosphere of the K supergiant would be in a similar state as the solar chromosphere.

There are three observational effects in favor of this last hypothesis. The first one is the long known Adams-Russell phenomenon which is the fact that the hydrogen lines in all late type supergiants are too strong for the spectral types. This effect can be explained by the superexcitation. For the system of ζ Aur I could show that one-half of all hydrogen atoms that contribute to the formation of the Balmer lines in the K spectrum will be excited in the chromospheric layers.

The second observation is by Odgers and Wright (1964). They showed that far outside eclipse there are considerable changes in the emission and absorption profile of the Ca II K line.

These changes are very similar to the changes of the K line on the solar disk, but the scale must be much larger. I would be quite surprised if these changes could be explained as an effect of B star radiation.

The third effect that shows changes in the K chromosphere is the different extent of the chromosphere. The height at which the first trace of chromospheric absorption of the K line has been observed changes by nearly a factor 3. For ζ Aur this normally happens 10-12^d before the beginning or after the end of total eclipse. Sometimes the first trace of a Ca II line was observed 40^d from second or third contact, sometimes the beginning was between these extremes. The chromosphere is not necessarily symmetrical: the extent can be different at ingress and egress. A relation of these changes with the period of the system has not been found.

Summarising I can say there are some effects that show that the outermost atmosphere of the K supergiants can have a structure similar to that of the solar chromosphere and perhaps the solar corona. The influence of the ultraviolet radiation of the B star cannot be completely neglected.

In my opinion two independent studies are necessary. The first is for the theoreticans, namely to study the ionisation effects of the diluted B radiation in detail and in addition to study the non-LTE effects in the atmospheres of K supergiants.

The second task is the spectroscopic observation of Balmer lines and the Ca II K line during the whole period and further observations of chromospheric eclipses with high dispersion.

REFERENCES

Groth, H. G. 1957, *Z. f. Astroph.* 43, 185.

Odgers, G. J., and Wright, K. O. 1964, *DAO Victoria Contr.* 89.

Wellmann, P. 1939, *Veröffentl. d. Universitäts-Sternwarte Babelsberg XII*, 4.

Wilson, O. C. 1960, *Stars and Stellar Systems*, 6, 436 (Compilation of all papers known to 1960).

DISCUSSION

Pecker: Is the apastron close to the eclipse or not? This could be important for effects that depend on the distances.

Groth: For all three stars the total eclipse is very near to the periastron.

Hillendahl: Does the magnitude of the K star change?

Groth: Observations during total eclipse show irregular changes up to $0^m.1$ in the blue.

Hillendahl: Did you use a velocity distribution in the chromosphere or only turbulent velocities?

Groth: I have used only turbulent velocities.

Wellmann: I have tried to represent the observed curve of growth introducing a velocity gradient. But the calculations show that only a very small gradient might be possible. A larger gradient would change the curve of growth completely.

Thomas: The large turbulence shows that the dissipation of mechanical energy is sufficient to heat the chromosphere. If this works, you are not forced to postulate clouds of high densities.

Groth: If you assume that the source for the high excitation is in the K atmosphere, it is not necessary to have clouds at all. That was already shown by Wellmann (1939) and in my paper (Groth 1957).

Underhill: There exist fluctuations of the intensity of the Ca II K line. I tried to find fluctuations of the intensities of the Fe I lines, but without success.

Groth: The fluctuations of the Ca II intensities are found mainly in the highest layers. These fluctuations may be due to inhomogeneities in the chromosphere of the K type star. The Fe I lines can be observed only near the limb of the K star, where the density fluctuations are very small.

Magnan: Another idea that can be put into the discussion is the possibility of a mechanical heating of the chromosphere of the K star. This could explain the ionisation equilibrium without the assumption of a cloudy atmosphere (Magnan, 1965, *Ann. d'Astrophys.* 28, 512.

Groth: In the paper by P. Wellmann (Veröffentl. d. Universitäts-Sternwarte Babelsberg XII, 4, 1939) it was already shown that the dissipation of the mechanical energy is sufficient to explain the "superexcitation" of the chromosphere of the K type star.

Hillendahl: There is no source for the mechanical energy and no mechanism to transport it to the chromosphere.

Wellmann: The mechanical energy is supported and transported by convection. The large turbulence velocity shows that it can reach the higher layers.