1956ApJ...123...44C

AN INTERPRETATION OF AE AQUARII

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Received August 8, 1955; revised September 19, 1955

ABSTRACT

The spectrum of AE Aquarii is discussed on the basis of spectrograms taken at the Lick Observatory, giving a dispersion of 130A mm at Hγ. The late-type component of this double star, classified on the Morgan-Johnson system, is found to be K5 IV–V. This classification, taken together with Joy's minimum value of 1$\odot$ for the mass of the star, indicates that a rapid evolutionary expansion may already have brought it to the point of filling one lobe of the zero-velocity surface passing through the inner Lagrangian point of the system. On this hypothesis, supported by the presence of narrow Ca II emission lines, the K star is found to eject material, some of which is collected by the blue companion The order of magnitude of the rate of this transfer of mass is estimated by three independent methods: (1) the theoretical Sandage-Schwarzschild rate of evolutionary expansion; (2) the observed luminosity of the blue star; and (3) the intensities of the narrow and broad emission features in Hδ. These estimates agree, yielding a rate of $\sim 10^{25}$ g/year. The density of material in the region surrounding the blue star is found to be, accordingly, $\sim 10^{-13}$ g/cc. It is suggested that the accretion of mass by the blue star is related to the outbursts of 2 mag. found by Zinner, and a possible connection with the U Geminorum type variables is pointed out.

I. INTRODUCTION

The recent discovery by A. H. Joy (1954*a*, *b*) that the flaring variable AE Aquarii is a spectroscopic binary of short period has led us to attempt an interpretation of this system. Joy has found that AE Aquarii consists of a pair of dwarf stars, one of spectral type K, having relatively narrow emission lines of H and Ca II, the other possessing a continuous spectrum with superimposed broad emission lines of H, He I, and Ca II. Two stars of the U Geminorum class, SS Cygni and RU Pegasi, were reported by him (1954*a*) to show similar spectral features and large radial-velocity variations, suggesting the possibility of binary motion. Thus it is not impossible that the explosive U Geminorum phenomenon requires, in some unexplained fashion, two stars in a short-period orbit as a necessary, though not sufficient, condition.

Despite the spectral similarity of these three stars, it should be noted that AE Aquarii does not appear to be a typical U Geminorum star when judged by its light-variability. Zinner (1938) found outbursts of 2 mag. (photographic) with a possible period of about 1 year. Henize (1949), Lenouvel (1952), and Lenouvel and Golay (1954) observed a strong tendency for "flickering" at minimum, with occasional flares up to 1 mag. The A.A.V.S.O. detected no major outbursts during 1953, its "AE Aquarii year" (Mayall 1954). If we suppose that the period-amplitude relation found by Kukarkin and Parenago (1933), as modified by Kopylov (1954), applies, the outburst corresponding to 1 year should be 5 or 6 mag. We would then conclude that either the period is more nearly of the order of 5–10 days or that AE Aquarii does not have bona fide U Geminorum outbursts. In either case the spectrum found by Joy certainly suggests that AE Aquarii is a close relative of such variables as SS Cygni and RU Pegasi.

The present discussion consists of an attempt to obtain a self-consistent model designed to explain the major spectroscopic features of AE Aquarii. The interpretation given here may be thought of as an alternative to that advanced by Joy. Briefly, the argument is as follows: It is proposed in Section II that the late-type star lies above the main sequence at K5 by such an amount that it fills one lobe of the inner zero-velocity surface surrounding the system. In Sections III and IV we follow the motion of material

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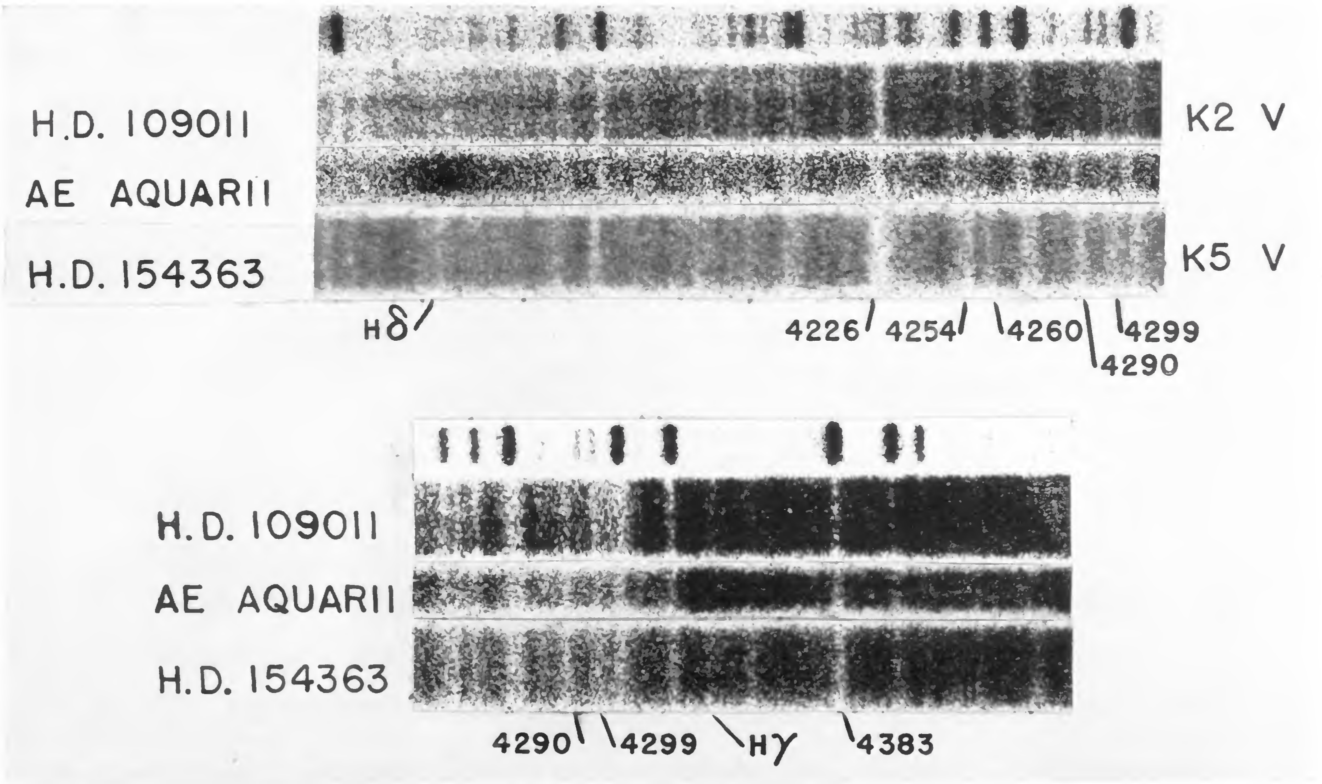

FIG. 1.—The spectrum of AE Aquarii compared with MK standards. The spectral type is thought to be K4 or K5 from the absence of the G band and the ratio of λ 4290 to λ 4299. The weakness of Ca I (λ 4226) and Cr I (λ 4254) suggests that the star is slightly above the main sequence.

flowing into the lobe surrounding the blue star. The density of gaseous material in this lobe (or, equivalently, the rate of accretion) is derived from the intensity of the broad Hδ emission and independently from the rate of accretion of this material by the blue star, the luminosity of which is found to be largely supplied by the kinetic energy of infall. An additional check on the density is obtained from the Sandage-Schwarzschild (1952) rate of evolutionary expansion of the K star. In Section V a possible process is briefly discussed through which the accretion of ionized material onto the blue component might engender, under suitable conditions, sudden releases of energy in the envelope, identifiable with the outbursts of U Geminorum stars.

II. THE SPECTRUM

The observational material is derived in part from the study made by Joy (1954*b*) and also from spectrograms taken at the Lick Observatory by G. H. Herbig, who has generously supplied them to us for use in this investigation. These spectrograms, giving a dispersion of about 130 A/mm at Hγ, were obtained with two prisms and a $3\frac{1}{2}$-inch camera attached to the 36-inch refractor. Suitable MK standards (Johnson and Morgan 1953; Johnson and Harris 1954) were taken for comparison purposes by one of us (R. P. K.) with the same prisms, camera, and slit-width.

One of these spectrograms of AE Aquarii, together with certain standard comparison stars, is reproduced in Figure 1. The general spectroscopic features pointed out by Joy, including the broad, unsymmetrical emission lines of hydrogen as well as the late-type absorption spectrum, are clearly seen. (The Ca II emission also is faintly present but is not reproduced.) Owing to the increasing opacity of the 36-inch objective toward the violet, the spectra of AE Aquarii are all very weak to the shortward of λ 4150 but are sufficiently dense in the vicinity of the G band to permit spectral classification. The spectrum reproduced in Figure 1, having the weakest continuous emission of the series, is the most suitable plate for the classification of the late-type star. Joy assigns it to dK0; we do not, however, find the corresponding classification K0 V when the star is placed on the MK system. The spectrum seems to be slightly anomalous, yielding different results from different line ratios. It can most nearly be described as K4 IV–V or K5 IV–V for the following reasons: (1) the G band is altogether absent; (2) the ratio λ 4290: λ 4299 is that of dK4 or dK5; (3) the resonance lines of Cr I, λ 4254, and Ca I, λ 4226, are too weak for K4 V–K5 V.

Possible systematic differences between the Mount Wilson and MK systems of spectral classification do not apparently account for the inconsistency, since, in general, the Mount Wilson system tends to classify K stars *later* than the MK system, e.g., HD 154363 is Mount Wilson dM0 (Wilson 1953); MK: K5 V. An inspection of Figure 1 shows that the ratio λ 4254:λ 4260 and the weakness of λ 4226 are closely that of K2 V, properties which seem inconsistent with criteria 1 and 2. These contradictions can, however, be removed by assuming that the star is slightly above the main sequence at K4 or K5. One might, of course, adopt the point of view that K0–K3 is the basically correct classification. Then the absence of the G band would again suggest that the star should be placed above the main sequence in that range. Thus, whether the star lies in the interval K0–K3 or the interval K4–K5, the properties of the spectrum seem to indicate a luminosity somewhat greater than class V. Further evidence on this point would be furnished by spectrograms reaching λ 4077 of Sr II.

We shall proceed, for illustrative purposes, on the assumption that the spectral classification is K5 IV–V, attempt to anticipate some objections that might be raised against it, and show how they may be answered. In the first place, it might be argued that the spectrum is composite; the filling-in by the blue star tends to wipe out such incipiently weak features as the G band, so that the late-type component is actually earlier than K5. Moreover, the weakness of Cr I and Ca I is in support of a classification of about dK0–dK2. The blue-star veiling, however, can have little effect on the ratio of the moderately strong features described in 2, and these lead to a classification at least as late as dK4.

A different kind of objection to the classification K5 IV–V might be looked for in the role played by the ionizing radiation of the blue star. Should the radiation field at the substellar surface of the K star be controlled by the blue star, a weakening of the lines of neutral metals, owing to ionization, might be thought to occur. This argument appears to be strengthened by the observed presence of hydrogen emission lines arising in an extended atmosphere associated with the K component, presumably excited by the radiation of the blue companion. We shall now consider the refutation of this objection.

Despite the dilution factor of the order of 10^{-4}, the blue star will control the radiation field at the substellar surface of the K companion and, in particular, should be responsible for a high degree of ionization of metals. The fractional projected area of the K-star disk exposed to the blue star is about one-fifth at elongation, the plate illustrated in Figure 1 having been taken just prior to that phase, K star receding. The net result will be that the K-star surface is divided into two parts, one large region controlled by the K star and a small one of totally foreign character. In no case can we think of this small ionized region as producing a *perturbation* on the spectrum of the star as a whole: its spectral properties are altogether different from those of the major portion of the surface. It therefore seems clear that the spectral classification obtained must be an integral property of the star.

A K5 V star has $T_e = 4400°$ K, $M_v = +7.8$ (Keenan and Morgan 1951), and a radius of 0.58 $R_\odot$, using Kuiper's (1938) empirical bolometric correction. From Joy's work, the minimum masses of the K star and blue star are 0.94 $\odot$ and 0.97 $\odot$, respectively, using the second of his two solutions (the first solution leads to even larger minimum masses). It does not appear likely that a K5 star can have a minimum mass of the order of 1 $\odot$ and remain on the main sequence. Present ideas of stellar evolution would lead to the belief that such a star is in a state of rapid expansion, proceeding essentially on the same time scale as that of a gravitationally contracting star of the same mass, luminosity, and radius. It is reasonable to suppose that the maximum attainable volume, namely, that of one lobe of the inner zero-velocity surface, has already been reached, and we shall go ahead on this assumption, which further results seem to justify.

There is, however, some direct observational evidence suggesting that the K star is surrounded by a turbulent gas envelope, an event to be expected if it is in a state of expansion through an inner zero-velocity surface. This evidence is the presence, in Joy's spectra, of narrow H and K emission lines sharing the radial velocity of the K star. These features are 2–5 A wide. The velocity of gases moving in the rotating frame of reference between the inner and outer zero-velocity surfaces can be readily estimated from the difference of potential of these surfaces, using the masses and separation of the stars adopted in this article. This gives a value of about 200 km/sec, in good agreement with Joy's observed width for the narrow emission features.

Generally speaking, Ca II emission is characteristic of SS Cygni stars and of objects in which considerable turbulence is believed to exist (supergiants of late spectral type, certain long-period variables, cepheid variables). It seems that turbulence is a likely mechanism for the production of such emission lines. It is also of interest to consider the case of TW Draconis. This is an eclipsing binary whose secondary is a subgiant listed by Crawford (1955) as filling the inner zero-velocity surface. Miss Roman has found Ca II emission lines, associated with the subgiant component, on a Yerkes spectrogram (Bidelman 1954). Several other eclipsing binaries with subgiant secondaries are known to show Ca II emission (RZ Eri, WW Dra, RT Lac, AR Lac), as are also several binaries with periods less than 1 day (W UMa, RW Com, RT And, FG Hya) (Bidelman 1954). It will be proposed in this article that the blue component of AE Aquarii is surrounded by a highly turbulent gas cloud. It is interesting to note that a strong, broad Ca II emission line shows the same radial velocity as the blue star, in agreement with the general idea that Ca II emission is a characteristic of turbulence.

In order to proceed further, we shall arbitrarily adopt Joy's second solution, which gives a mass ratio of unity (1.0) and a minimum mass of 1 ⊙ for each star. On the other hand, the mass of the K star can hardly exceed 1.5 ⊙ if it is to be classified as K5 IV–V. The system is not known to eclipse, but this may very well be disguised by the persistent flickering, of the order of 0.3 mag. (Henize 1949; Lenouvel 1952; Lenouvel and Golay 1954). For a mass ratio of 1.0, the dimensions of the inner zero-velocity surface given by Kopal (1954) permit an avoidance of eclipse if the masses of the stars are not less than 1.3 ⊙. We shall therefore adopt this value in the discussion to follow. It should be emphasized that none of the conclusions reached in this article are affected by the exact choice of the mass in the interval 1.0–1.5 ⊙. The "physical radius" (Kuiper 1941) of the K5 star would then be 1.2×10^{11} cm = 1.7 $R_\odot$ (about three times the radius of a main-sequence star of the same spectral type), the separation between the centers of mass 3.2×10^{11} cm = 4.5 $R_\odot$, and $i = 64^\circ$. The absolute bolometric magnitude of the K5 star becomes +4.8 if $T_e = 4300^\circ$ K, and $M_v = +5.5$, i.e., the star is 2.3 mag. above the main sequence. The parallax is then 0″.013, and we have, according to Joy, $M_v = +6.5$, with $R = 6.6 \times 10^9$ cm for the blue star.

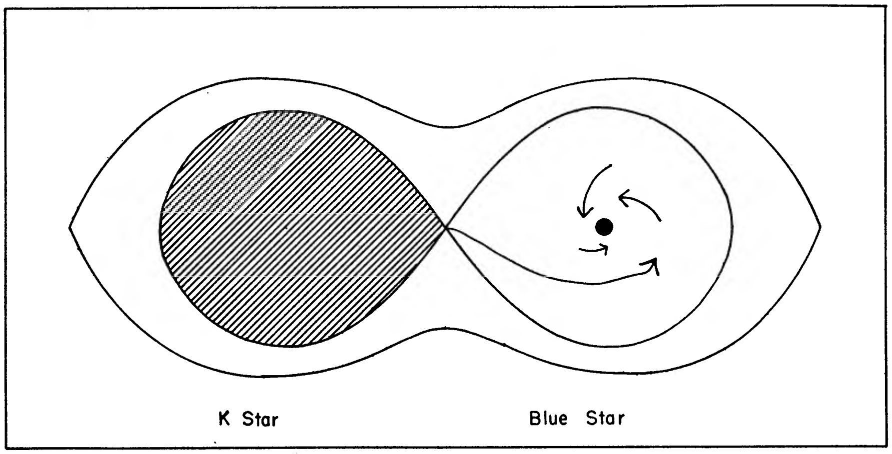

FIG. 2 —The system of AE Aquarii (schematic). The view is pole-on, and the inner and outer zero-velocity surfaces are indicated. Turbulent gas streams are represented by arrows.

The model as viewed "pole-on" is shown in Figure 2. As has already been suggested, two consequences of the filling of one lobe by the K star are the following: (1) A stream of gas will be ejected from the K star into the region surrounding the blue star, in a manner analogous to the "ejection of type A" described by Kuiper (1941) in connection with his interpretation of β Lyrae. The simultaneous ejection of material into the region between the inner and outer zero-velocity surfaces can, however, by no means be ruled out and is probably to be expected. (2) The K star will suffer a decrease in surface gravity when compared with a single star of the same mass and radius. Such a reduction will tend to increase the degree of ionization, and, in particular, the conversion of chromium from Cr II to Cr I and calcium from Ca II to Ca I will be delayed as one passes from K0 to K5. Thus Cr I, λ 4254, and Ca I, λ 4226, are weakened, as we have already indicated.

Dr. Joy (private communication) has expressed the opinion that the K star is certainly earlier than K5. In this connection it should be pointed out that the spectrum reproduced in Figure 1 is rather narrow. There is also some question regarding the use of the MK system of classification in attempting to detect comparatively small luminosity effects. It seems that this disagreement over the assignment of spectral class is in a large part due to the fact, recognized by Joy and the authors, that the late-type spectrum is peculiar. This in itself lends plausibility to the hypothesis that the star is somewhat swollen. It should be emphasized in particular that, if Joy's classification (dK0) is adopted, the average radius of such a star would be about half that of the inner lobe, and an increase in this radius by a factor of 2 would be beyond the limit of spectroscopic detectability at low dispersion. There is, therefore, in any case, no obstacle to the hypothesis that the K star does indeed fill a lobe of the inner zero-velocity surface.

III. DISCUSSION OF THE PROCESS OF MASS TRANSFER

According to modern ideas on stellar evolution, the expansion of a star is intimately related to the gravitational contraction of a hydrogen-depleted central core, the luminosity being due chiefly to the conversion of hydrogen in a thin shell surrounding the core (Schönberg and Chandrasekhar 1942; Sandage and Schwarzschild 1952). The expansion occurs at a rate given essentially by the gravitational time scale, meaning that a certain fraction of the total energy released is converted into potential energy of the outer regions of the stellar mass. When, as in the present case, the size of the star is limited by a zero-velocity surface, the consequence of the tendency to expand must be the outpouring of mass through this surface, especially through the conical tip of the star at the inner Lagrangian point, where a natural sink for the flow of material exists. This ejected material will then be accelerated in the gravitational field of the companion star (here the blue star) and captured, as will be shown later.

In order to estimate roughly the rate σ at which mass is emitted by the K star, we can equate the order of magnitude of the rate of increase of potential energy to the luminosity thus:

$$\frac{G}{2R}\frac{d}{dt}(\mathfrak{M}^2)=\frac{G\mathfrak{M}\sigma}{R}\sim L. \tag{1}$$

The potential of the ejected material is that associated with the inner Lagrangian surface and is significantly smaller in magnitude than the mean potential energy per unit mass of the star. We are therefore justified in neglecting to include it in the order-of-magnitude relationship expressed by equation (1). This relationship presumably gives the order of magnitude of σ. We obtain in this way the value 6.7×10^{25} g/year, using the adopted values of L, $\mathfrak{M}$, and R for the K star. However, for an isolated expanding star, the results of Sandage and Schwarzschild (1952) indicate that, for a mass of 2 $\odot$, the total rate of increase of potential energy is about thirty times smaller than the luminosity. It is not possible to state whether or not a factor of this order is applicable in the present case. If this were so, the accretion rate would become 0.2×10^{25} g/year, a value which is smaller than, but closer to, the two independent estimates of σ obtained later.

As a check on this procedure, an alternative estimate was made on the basis of the radial expansion of the models of Sandage and Schwarzschild (1952). Although given only for masses 1 $\odot$, 2 $\odot$, and 4 $\odot$, the physical characteristics of these models can be readily interpolated for intermediate masses. This was done for the adopted value, 1.3 $\odot$. If $\dot{R}_m$ is the rate at which the radius of the (single-star) model increases, an estimate of the corresponding rate of mass loss σ of our (double-star) component filling the inner Lagrangian surface is given roughly by

$$\sigma = 4\pi R_m^2\bar{\rho}\dot{R}_m ,$$

where $\bar{\rho}$ is the mean density of the model. This can be written

$$\sigma = 3\,\mathfrak{M}\frac{\dot{R}_m}{R_m}.$$

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Values of $\dot{R}_m$ were obtained by numerical differentiation for all but one of the models considered by Sandage and Schwarzschild, and the corresponding values of σ listed in Table 1 are in general agreement with the previous estimate. It is hard to see physically how the rate of mass loss by an expanding member of a close binary system can ever greatly exceed the value given by equation (1).

The inner zero-velocity surface surrounding the blue star will contain the matter ejected from the K star in the neighborhood of the inner Lagrangian point L_1. This matter will be accelerated by the blue star to velocities of several hundred kilometers per second. Kuiper (1941) has discussed a similar system (type A) and states that the material ejected from the expanding star forms a ring around the companion. The high angular momentum of the infalling material relative to the blue star appears, at first, to offer an obstacle to a significant rate of accretion. It is easy to show, however, that for AE Aquarii the collision mean-free path in the region around the blue star is very much smaller than the dimensions of the zero-velocity surface. As a consequence, the material moves like a gas. The Reynolds number is extremely high, and it is quite certain that the gas is turbulent. If, in fact, a ring is formed, as Kuiper suggests, the inner portions of the ring must rotate more rapidly than the outer portions, as both describe essentially circular Keplerian orbits around the blue star. The velocity gradient will cause a very rapid turbulent exchange of angular momentum, so that the inner part of the ring will lose angular momentum and move in closer, while the outer part gains angular momentum and spreads out. The constant infall of new material keeps the expansion of the ring in equilibrium, and the net effect is that matter accretes onto the surface of the blue star, which acts as a sink for the angular momentum as well. The mixing length in the ring is extremely large, being, according to Prandtl's theory, of the order of the dimensions of the ring itself. It is of some interest to estimate the size that the ring would have, were it not for the dissipative effect of turbulence. A particle of unit mass, falling out of the K star at the inner Lagrangian point, will possess initially an angular momentum relative to the blue star equal to Va, where V is the velocity of the star and a the radius of its orbit. The order of magnitude of this angular momentum cannot be expected to change during the time it takes for the particle to come close to the blue star. If p is the distance of nearest approach to the blue star, and v is the velocity of the particle, we can write

TABLE 1

	MODEL NO.					
	I	II	III	IV	V	VI
$\sigma\times 10^{-25}$ g/year	0 19	0 87	1 35	1 66	2 42	4 90

$$Va\sim p\,v=p\,\sqrt{2G\mathfrak{M}p^{-1}}\,.$$

We find in this way $p\sim a/8=2\times 10^{10}$ cm, a value about three times larger than the radius of the blue star. This represents the order of magnitude of the periastron distance of the infalling matter, neglecting the effects of turbulence. Finally, to support our statement that the material forms a turbulent gas, we shall estimate the collision mean-free path. A lower limit to the density is obtained by assuming that the blue star forms a perfect sink. In this case, at a typical distance of 6×10^{10} cm from the blue star, the velocity acquired is about 760 km/sec. This must also be the order of magnitude of the accretion velocity. Assuming this and an accretion rate of 10^{25} g/year, the continuity condition for the steady state yields a density of $\sim 10^{-13}$ g/cc. As the gas is ionized, the cross-sections will be larger than those for neutral atoms, which are about 10^{-16} cm^2. Even in this case, however, the mean free path is only 10^5 cm. The Reynolds number is extremely high, being about 10^7.

Finally, the repulsive force exerted on the infalling gas by the blue-star radiation is estimated to be smaller than the gravitational attraction by a factor $\sim 10^{-3}$. There appears, therefore, to be no obstacle to the hypothesis that the blue star collects material ejected by its companion.

If, in fact, as the foregoing considerations suggest, mass is accreted by the blue star at a rate of the order of 10^{25} g/year, we would expect that the kinetic energy of the tenuous infalling material would be dissipated into heat by viscosity in the turbulent motion and by impact with the denser material of the star's atmosphere. The heat thus liberated should then appear as a contribution to the luminosity of the blue star of about the amount $L = G\mathfrak{M}\sigma R^{-1}$.

The adopted luminosity for the blue star is 4.9×10^{33} ergs/sec. The value of σ obtained by substituting this figure in the relation $L = G\mathfrak{M}\sigma/R$ is 0.6×10^{25} g/year. The agreement of this value with the other estimates suggests that the observed luminosity of the blue star is essentially due to the energy released by the accreted material. This view is strengthened also by the fact that the blue star occupies a peculiar position in the H-R diagram. It lies 10.5 vis. mag. below the main sequence but about 4 mag. above the most luminous white dwarfs, whose effective temperature it exceeds by about 8000° K. Unless the blue star is essentially degenerate, it can readily be shown that the small radius implies such a high internal temperature that electron scattering is the principal source of opacity. A simple calculation based on the standard model then yields a luminosity 8 mag. brighter than is observed.

AE Aquarii is an example among many other close binary systems in which the ages of the two components appear to differ greatly. The process of mass loss by expansion through an inner zero-velocity surface (Kopal 1955) affords a possible explanation for this apparent anomaly in the case of eclipsing systems with subgiant components (Crawford 1955).[1] The history of AE Aquarii, according to this view, could be described as follows: Originally the blue star was the more massive component. As evolution proceeded, it began expansion earlier than its companion, losing the hydrogen-rich material from its outer layers. Eventually it became essentially depleted of hydrogen and contracted to its present state. Later on, the companion, which must have been more massive and more luminous than it appears at present, also expanded until it reached the inner zero-velocity surface and initiated the process of mass loss which is still going on. The existence of evolutionary sequences of this type in close binary systems is strongly suggested by the currently accepted theories of stellar evolution.

IV. THE HYDROGEN-EMISSION LINES

A third way of estimating the accretion rate, which yields about the same value as the other two, is provided by the total intensity of the hydrogen-emission lines, which show the radial velocity of the blue star. For this purpose the line Hδ, in the spectrum reproduced in Figure 1, was utilized. Allowing for a correction due to the contribution of the K5 star to the continuous spectrum, the effective width $\Delta\lambda$ of Hδ was found to be 23 A for a height set equal to the intensity of the blue-star continuum. The hydrogen was assumed to be completely ionized (in agreement with the fact that the observed emission lines show no self-absorption) at constant density in a sphere of radius S surrounding the blue star. The assumption of constant density was, of course, made for convenience. However, because of the difficulties caused by the effects of turbulence, a better guess would be hard to make. It is probably true that turbulence tends to make the density more uniform than it would otherwise be. The temperature of the blue star being 20000° K, an electron temperature of 10000° K was arbitrarily assumed.

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[1] The process of mass ejection and its effect on the period have also been discussed by F. B. Wood (1950; see also Dadaev 1954).

The rate of radiative recombination of ionized hydrogen into different energy levels has been calculated by Cillié (1932) for several assumed temperatures. The rate of recombination per cubic centimeter at 10000° K into the sixth level is given by him as $1.45 \times 10^{-14} N^2$, where N is the density of hydrogen nuclei, assuming that all electrons come from the ionization of hydrogen. The probability that the excited atom will emit a quantum in Hδ is 0.221. The density N is then given by the expression

$$0.221 \times 1.45 \times 10^{-14} \times \frac{4\pi}{3} S^3 N^2 = \frac{8\pi^2 R^2 c}{e^{hc/\lambda k T} - 1} \frac{\Delta\lambda}{\lambda^4},$$

where T is the effective temperature, R the radius of the blue star, and λ the wave length of Hδ. We obtain in this way

$$N^2 S^3 = 1.3 \times 10^{56} . \tag{2}$$

This figure is overestimated because of the neglect of the effect of captures in levels higher than the sixth, followed by cascading into the sixth level. If, at the other extreme, we assume that all captures in levels above the sixth result in cascades to this level, we obtain the value 1.9×10^{55} for N^2S^3. Strömgren's theory (1939) gives a relation between the density of hydrogen and the radius of the largest sphere, S_S, ionized by the blue-star radiation:

$$N^2 S_S^3 = 1.0 \times 10^{55} . \tag{3}$$

As this value is perhaps significantly smaller than the one given by equation (2), there is an indication that another mechanism besides blue-star radiation is at work keeping the gas ionized, in fact, all the way to the neighborhood of the K star, where the narrow hydrogen emission arises. Turbulence may very well provide such a mechanism. The fact that Hδ is observed and shows no self-absorption makes it clear that no H I region envelops the ionized zone, so that S should be taken as the effective radius of the outer zero-velocity surface, beyond which the density can be assumed to decrease abruptly. This radius is about 1.6×10^{11} cm. Substituting this value in equation (2), we get for N the value 1.8×10^{11} atoms/cc, yielding the value 4.0×10^{-13} g/cc for the density ρ on the assumption of a hydrogen abundance of 75 per cent. The velocity v given by the Hδ line at half-maximum is 400 km/sec, corresponding to a free-fall distance r from the blue star of 8×10^{10} cm. The order of magnitude of the accretion rate is given by the relation

$$\sigma = 4\pi r^2 \rho v .$$

In this way we obtain for σ the value 4.4×10^{25} g/year. This is overestimated, owing to the neglect of cascading. If all cascading is assumed to populate the sixth level of hydrogen, we obtain for N the value 2.6×10^{10} H atoms/cc and for σ the value 0.6×10^{25} g/year.

There is also a narrow Hδ component in emission (2–5 A). Its radial velocity was not measured by Joy but is apparently similar to that of the K star. Its intensity on the spectrogram in Figure 1 seems about one-fifth that of the broad line. This is in agreement with the mass-transfer picture of AE Aquarii, according to which the region between the inner and outer zero-velocity surfaces surrounding the K star is expected to be filled with material of about the same density as the gas in the lobe surrounding the blue companion. This is, of course, because of the condition for the continuity of gas flow, since the velocities characteristic of the two regions are of the same order of magnitude.

It seems possible that turbulence keeps hydrogen ionized even in the shadow cone behind the K star. If not, we would expect the radial velocity of the narrow hydrogen-emission features to be systematically smaller than that of the K component. Spectrograms taken with a higher dispersion than was available to us are needed to settle this question.

To summarize, we have obtained values of the accretion rate from three independent lines of approach: (1) the theory of expansion; (2) the luminosity of the blue star; and (3) the recombination of hydrogen and have found them to have the same order of magnitude. This agreement seems to constitute a good argument in favor of this proposed model of AE Aquarii.

V. FURTHER DISCUSSION

In a recent publication (1954) Ambarzumian has reviewed the observational evidence relating to sources of stellar energy and has concluded that thermonuclear processes in stellar interiors are insufficient to explain a wide variety of unusual stars (T Tauri stars, comet-like nebulae, certain irregular variables of low luminosity, etc.). He has suggested that additional energy sources should be looked for in the outer regions of such objects. This general point of view seems to receive some further support from our conclusion that the luminosity of the blue component of AE Aquarii is mostly the result of the infall of material onto the surface.

The discovery of outbursts in AE Aquarii by Zinner (1938) hints at a possible relationship between this star and the U Geminorum group. What is further suggested by the preceding model is a connection between the process of mass transfer and the existence of outbursts. There is evidence that the outbursts are probably associated with the blue star: the spectrum is similar to that of an old nova; the magnitude fluctuations observed by Lenouvel (1952) in the photographic region are probably associated with the blue star; and, finally, there is no evidence that other systems in which one component fills the inner zero-velocity surface and the other component is a main-sequence star or a subgiant exhibit outbursts.

With regard to the process through which outbursts in the luminosity of the blue star result from the accretion of matter, a suggestion by Greenstein (1950) in connection with the T Tauri variable BD$-6^\circ 1253$ is of interest. The density and velocity of the dark cloud in the immediate vicinity of this star have values quite close to those found by us in the region surrounding the blue component of AE Aquarii. Greenstein points out that the magnetic field whipped up by the turbulent motion of the accreted ionized gas will itself be accreted, with the possibility of resulting intense electrical discharges identifiable with the flares observed in this T Tauri object. A similar mechanism may be operating in AE Aquarii.

In this connection the work of Kopylov (1954) is of interest. He has shown that the period-amplitude relation for certain recurrent novae is not necessarily a simple extrapolation of that for the U Geminorum variables. It would therefore seem possible that the mechanism responsible for the outbursts of AE Aquarii and stars of the U Geminorum class need not be identical in kind with that responsible for the explosions of repeating novae.

We wish to record our appreciation to Dr. G. H. Herbig for making available to us his spectrograms of AE Aquarii and also to thank Dr. W. P. Bidelman for a valuable discussion. We are indebted also to Dr. A. H. Joy, to Dr. J. L. Greenstein, and to Dr. A. R. Sandage for reading the manuscript and commenting on it. We are especially grateful to Professor O. Struve for his criticism.

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