shows that these two groups of OB stars are expanding (there is a large spread of the velocities) and are approaching each other with a mean velocity of about 4 km/sec. This fact can be regarded as an additional proof of their mutual independence.

I thank Professor L. V. Mirzoyan for constant interest in the work.

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VARIATIONS IN THE LIGHT OF WW Vul AND THEIR INTERPRETATION

G. V. Zaitseva and P. F. Chugainov

The results are given of photoelectric measurements of the light of the fast irregular variable WW Vul made during 1967-1982 in the UBV system. Several fadings of the light of duration ~10^7 sec with amplitude reaching $2^m.2$ in V were observed; on these were superimposed lesser fadings of duration ~10^6 sec. It is shown that the variations in the light of the star in the UBV bands can be explained by changes in the extinction in a circumstellar dust envelope of radius $1.5 \cdot 10^{13}$ cm and grains of dust having radii 0.16 μm. The observed excesses of the radiation of the star in the region 1.65-3.4 μm can be explained by thermal emission of the grains at temperature 800-1000°K. The numbers of grains determined on the basis of their extinction and on the basis of the thermal emission are approximately the same. It is estimated that the total number of grains is 10^{36}-10^{37} and the corresponding mass 10^{22}-10^{23} g. It is argued that in the envelope of WW Vul there is probably heated gas, whose radiation is superimposed on the emission of the star.

1. Introduction

The present paper continues investigations of the variations in the light of irregular variables (see [1-3]). We give here all our photoelectric observations in the UBV system of the star WW Vul, which is regarded as a rapid irregular variable of the

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type A3e [4, 5]. At the position of the star itself there is no dark nebula [6]. To interpret the variations in the light of this star in the UBV bands, we propose a model of a circumstellar dust envelope in which the radii of the dust grains are approximately 0.16 μm. The same model can be also be used to interpret the photometric data on the emission of WW Vul in the infrared region published in [3].

The first evidence for the existence of circumstellar dust envelopes of T Tau stars and irregular variables of early types was given by Mendoza and Poveda [7-9]. They showed that grains heated by the radiation of the star are probably the source of the infrared radiation of such stars. Cohen [10], and also Cohen and Kuhi [11] confirmed this conclusion for the majority of the investigated stars. The recently published papers [12-14] develop very similar ideas about the structure of the circumstellar dust envelopes of T Tau stars and the irregular variable HR 5999 of early type. Both for the T Tau stars and HR 5999 it is shown that the observed optical characteristics correspond to dust grains with a radius of order 0.1 μm. However, Wenzel, et al. [15, 16] assume that in the case of rapid irregular variables the fadings of the light are due to stable circumstellar clouds of meteoritic particles much larger than dust grains (with a radius of order 20 cm). Pugach [17] explains the variations in the light of the rapid irregular variable RZ Psc by the appearance of a hypothetical absorbent. The model we consider is basically similar to the models of [12, 14].

Comparison of the V magnitudes and the color indices (B − V) and (U − B) observed in WW Vul at different times shows that the variations of the fluxes in the UBV bands are due probably to, not one, but two (or more) causes (see [18] and Sec. 2 of the present paper). Thus, it is possible that the results of our calculations, made under the assumption that the changes in the light of the star in the UBV bands are due solely to changes in the extinction of the dust, only partly explain the observed variability of WW Vul. This is confirmed by the observation by Timoshenko and Filip'ev [18] of changes in the line profiles and the energy distribution in the spectrum of WW Vul, the origin of which is probably not solely to be associated with dust extinction. However, our results, based on the model of a circumstellar dust envelope, are fairly close to reality, and this suggests to us that dust extinction in the main, if not the only, cause of the variations in the light of WW Vul. We also advance some ideas about a second cause of the variations in the light — emission of circumstellar gas.

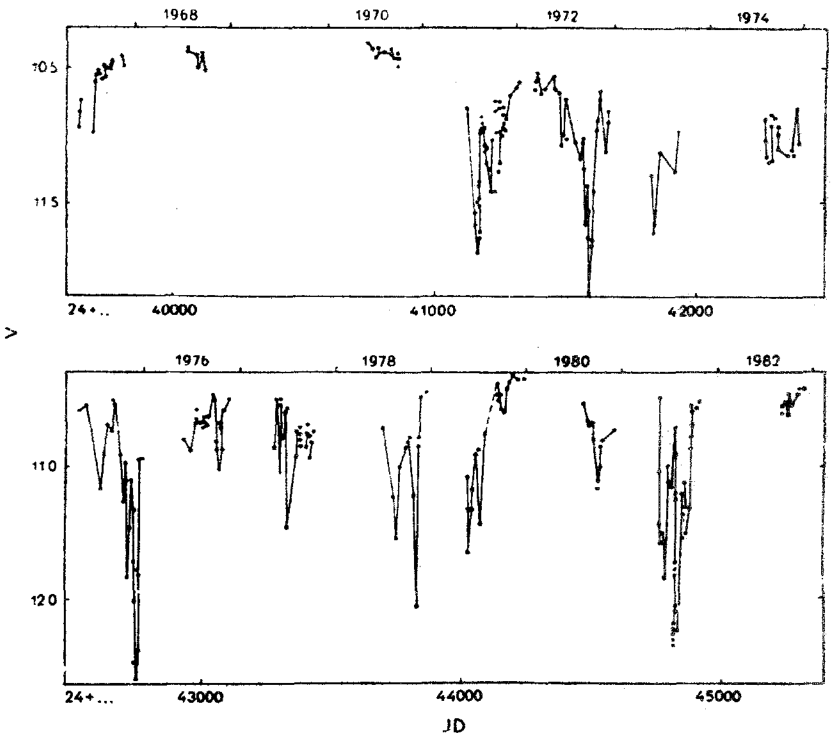

Fig. 1. Light curve of WW Vul.

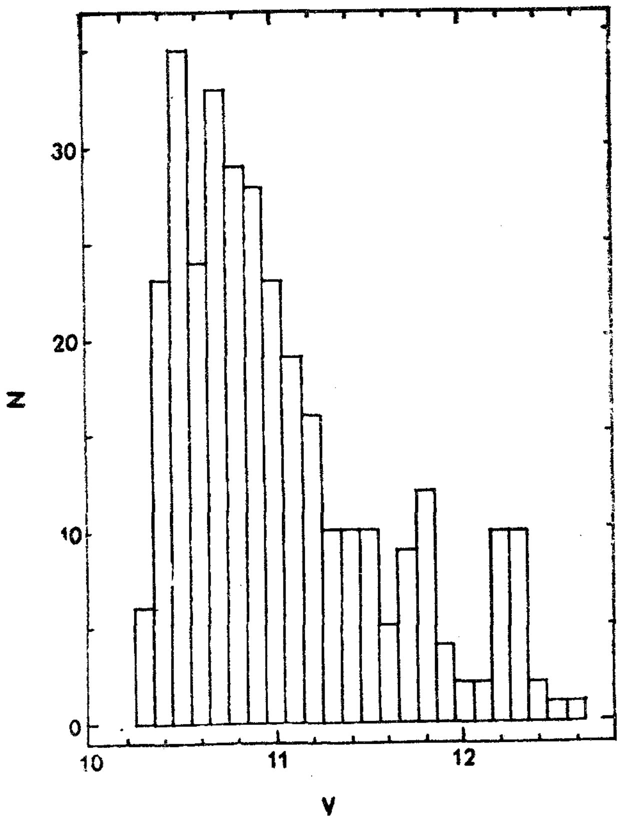

Fig. 2. Distribution of the numbers N of observed V magnitudes of WW Vul.

2. Results of Observations in the UBV System. Characteristics of the Light Variations

Photoelectric UBV observations of WW Vul were made by one of the authors (G. Z) at the Crimean Station of the P. K. Shternberg State Astronomical Institute using the 60-cm reflector and an automatic electrophotometer. A small fraction of these observations has been published earlier [3, 19, 20]. Since then, the magnitudes of the comparison stars have been determined more accurately. Here, we consider the results of all our UBV observations of WW Vul up to 1982 inclusively; we intend to publish separately a table containing the V magnitudes and the color indices (B — V) and (U — B). The errors of the observations were $\pm 0\overset{m}{.}01$ for V and the color index (B — V) and were in the interval $\pm 0\overset{m}{.}02$-$\pm 0\overset{m}{.}03$ for the color index (U — B).

Figures 1 and 2 give the light curve of WW Vul in V and a histogram constructed using the observed V magnitudes. It can be concluded that the maximal brightness is $V \approx 10.3$-10.4 and is reached rather seldom, only in intervals of time of relative duration $\leqslant 0.1$. For the remainder of the time the light is reduced, the depth of the fadings being between $0\overset{m}{.}1$ and $2\overset{m}{.}2$. Fadings not exceeding $0\overset{m}{.}9$ are the ones most often observed. The fadings are partly superimposed or succeed one another, and their duration is from several days to 100-200 days, i.e., $\sim 10^6$-10^7 sec. It should be noted that the fadings we observed in 1972, 1975, and 1981 are deeper than the ones noted in the observations of other authors.

It can be seen from Figs. 3 and 4 that the fadings are accompanied by an increase in the color indices (U — B) and (B — V). On the average, this dependence is steeper for fadings of smaller amplitude. However, the spread of the individual measurements is appreciably greater than their error, so that there is not a single-valued dependence.

3. Extinction of the Circumstellar Dust Envelope in the UBV Bands

Rossiger and Wenzel [16] showed that the V magnitude and color indices (U — B) and (B — V) observed at the light maxima of WW Vul correspond to the spectral type A3eα of

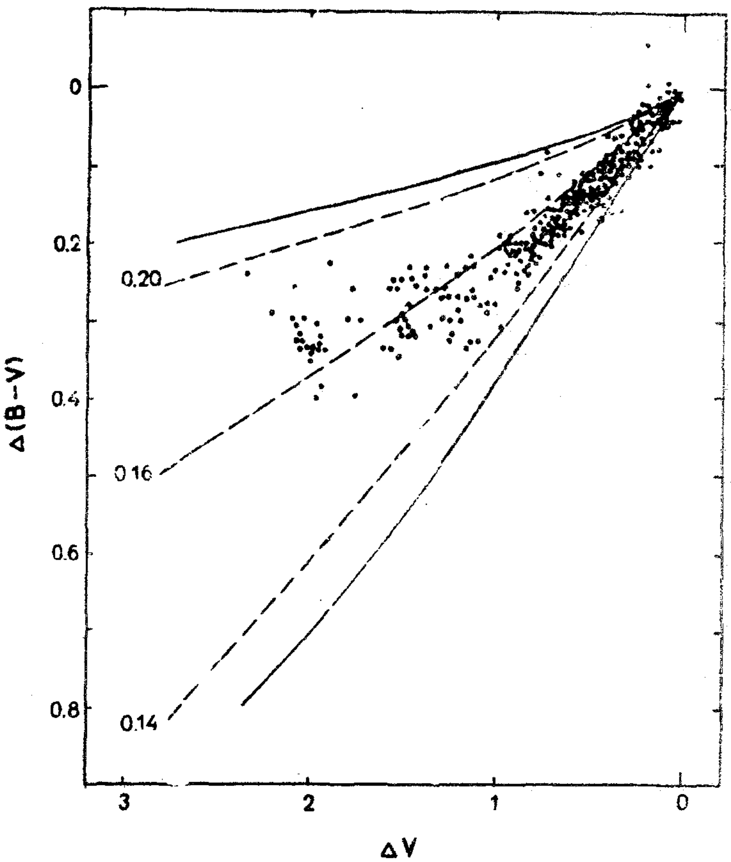

Fig. 3. Dependences between the variation $\Delta(B - V)$ in the color index and the variation ΔV in the magnitude. The differences between the observed $(B - V)$ and V and their values at the brightness maximum are shown by the points. The theoretical dependences are for an envelope consisting of grains of constant radius a, the continuous curves for planar geometry and the broken curves for spherical geometry. The corresponding values of a in μm are given next to the curves.

this star and interstellar extinction characterized by color excess $E(B - V) = 0.3$ and light fading $A_V \approx 1^m$ [16]. We used somewhat different values for the magnitudes and color indices for the brightness maxima of WW Vul, namely, $V = 10.30$, $(B - V) = 0.30$, $(U - B) = 0.25$ and, using Johnson Q method, determined from them the spectral type A2 V, $E(B - V) = 0.23$, $A_V = 0.74$. In all cases when we observed WW Vul to have V, $(B - V)$, $(U - B)$ values exceeding the given values we assume they are changed by the extinction of the circumstellar dust envelope.

Since anomalies in the chemical composition were not found in the spectrum of WW Vul, we assume that the dust grains in the circumstellar envelope are formed (or were formed) by condensation of a gas of normal composition, i.e., they are silicate grains. We have used the theory of the condensation of grains reviewed by Yamamoto and Hasegava in [24].

In our calculations, we used the comparatively simple theory of radiative transfer in a circumstellar dust envelope developed by Code [25]. Although the absorption of light by the grains leads to their being heated, their temperature is probably sufficiently low to assume that their own emission in the UBV bands is negligibly weak. The relations between the optical thickness and the fading of the light of the star in the envelope in the UBV bands were obtained for two cases: a) spherically symmetric and b) geometrically thin spherically symmetric envelope. In both cases, we assumed isotropic nonconservative scattering by grains of constant radius a.

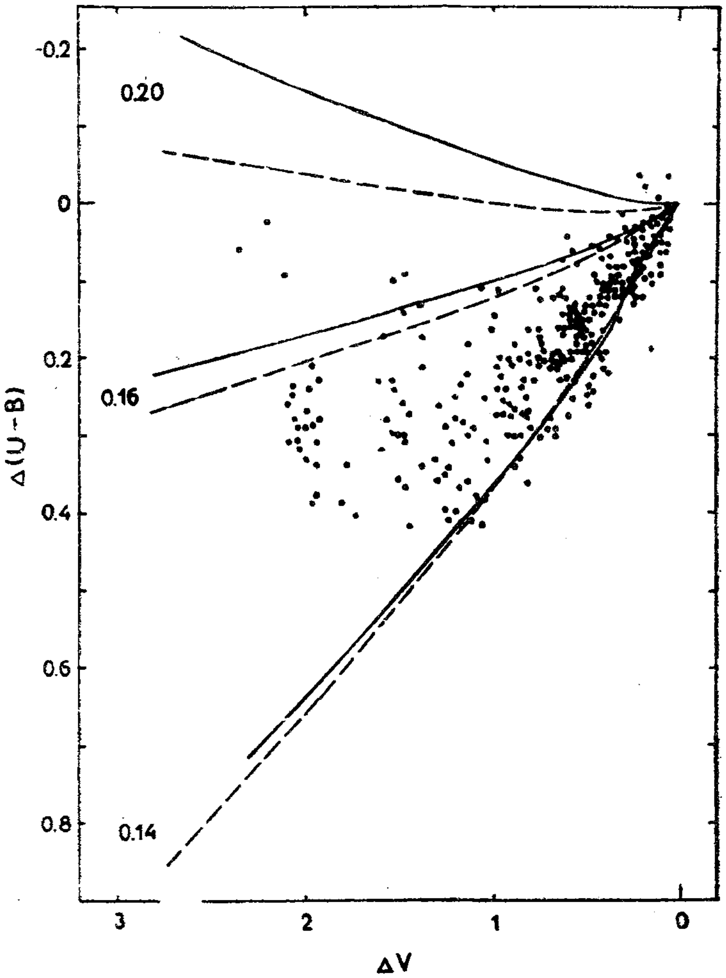

Fig. 4. Dependences between the variation Δ(U − B) in the color index and the variation ΔV in the magnitude. The results of the observations and calculations are denoted as in Fig. 3.

If we denote by $\varkappa$ the coefficient of absorption per unit mass and by σ the coefficient of scattering per unit mass, then the optical thickness in the envelope is determined as

$$d\tau = -(\varkappa + \sigma)\, ds,$$

where s is the distance. The transfer equations in the envelope are solved, as in [25], for the following boundary conditions. Let τ_1 be the optical thickness of the envelope, I_* be the mean intensity of the radiation of the star, and I_+ and I_- be the mean intensities of the radiation in the envelope traveling outward and reflected inward, respectively. It is assumed that at the outer edge of the envelope

$$I_-(0) = 0.$$

The radius of the inner surface of the envelope is assumed fairly large compared with the radius of the star, so that for the radiation reaching the inner boundary

$$I_+(\tau_1) = I_* + I_-(\tau_1).$$

The ratio of the luminosity of the star after passage of the light through the envelope to the luminosity of the star without envelope was found in two different ways. In the case of spherical geometry, we used the relation (9) derived in [25] by solving the transfer equation in the Schwarzschild approximation. For planar geometry, we used equations (IX.3)-(IX.5) in Chandresekhar's monograph [26] for a normally entering flux ($\mu_0 = 1$), and the numerical values of the functions $X(\mu)$ and $Y(\mu)$ were taken from the tables of [27]. First, for different angles μ and unit flux incident on the inner boundary of the envelope we calculated the intensities of the radiation reflected and diffusely transmitted by the envelope, and we found the fluxes corresponding to them. Then, by iteration, we simultaneously found the mean relative intensities of the radiation incident on the inner boundary of the envelope and diffusely transmitted by it: $[I_* + I_-(\tau_1)]/I_*$ and $I_+(0)/I_*$, respectively.

To make these calculations, it is also necessary to know the dependence of the complex refractive index $m' = n - ik$ on the wavelength λ. The quantity m' occurs in the exact expressions of Mie's theory for spherical grains (see [28]), and we used them to determine the values of the scattering and absorption coefficients. Exact numerical values of m' for silicates are known only from laboratory measurements for pure substances. However, in calculations of models of circumstellar envelopes it was found that the grains probably have much higher absorption in the visible and near infrared regions of the spectrum than in the case of pure silicates [29]. This is attributed to "contamination."

Our calculations led to the same result for WW Vul, and we therefore decided to use values of n and k close to those used in [29]: $m' = 1.55-0.1i$ for $1\ \mu m \leqslant \lambda \leqslant 3\ \mu m$ and $m' = 1.55-0.063(\lambda)^{1/2}i$ for $\lambda \geqslant 0.55\ \mu m$ [12]. We made several series of calculations, taking a constant value of n and choosing the values of k and the grain radius a in such a way as to reproduce the changes observed in WW Vul of the color indices $(B - V)$ and $(U - B)$. It was found that the dependence $m' = 1.55-0.063(\lambda)^{1/2}i$ in the region $0.36\ \mu m \leqslant \lambda \leqslant 0.55\ \mu m$ is quite incompatible with the observations. The assumption that k is constant within the region covered by the UBV bands and has a value between 0.05 and 0.1 makes it possible to represent the observed dependences either between V and $(B - V)$ or between V and $(U - B)$, but not both these dependences at once, for grain radii that do not differ too strongly. Correspondence with the observations was achieved for grain radii in the interval 0.14-0.20 μm and the following values of k: 0.05 for V, 0.06 for B, and 0.07 for U; we took $n = 1.65$.

This result agrees with the conclusion of Herbig [30] that for the interstellar grains k increases for $\lambda \leqslant 0.44\ \mu m$. The data given in [31] indicate that the increase in k with decreasing λ in the region $0.36\ \mu m \leqslant \lambda \leqslant 0.55\ \mu m$ can be due to the presence in the grains of the oxide SiO, but this must be verified by calculations of models of grains.

In Figs. 3 and 4 the observed variations in the light and the color indices,

$$\Delta V = V - 10.30, \quad \Delta(B-V) = (B-V) - 0.30, \quad \Delta(U-B) = (U-B) - 0.25$$

are compared with the values calculated for circumstellar dust envelopes with different optical thicknesses. The steepness of the dependences calculated for constant radius a differ quite appreciably from the steepness of the mean observed dependence, particularly for fadings ΔV in the range 1^m-2^m. This could be due to each of the fadings being caused by concentrations of particles of somewhat different sizes. Thus, the mean dependences between the brightness and the color indices could be brought into complete agreement with the calculated dependences by assuming that the fadings of V in the intervals 0^m-1^m and 1^m-2^m are due to grains whose radii are, respectively, 0.14-0.16 μm and 0.16-0.20 μm. However, the differences in the grain sizes obtained in this way are small and, in addition, there is probably also an uncertainty associated with the fact that the dependences of the color indices $(U - B)$ and $(B - V)$ on V are not single valued (see Sec. 2). Further (see Sec. 5) we note that the spread of the points in Figs. 3 and 4 may be due not only to differences in the grain sizes but some other cause.

Ignoring the possible differences in the grain sizes, we estimate the mean number N_s of grains in a column with section 1 cm^2 intersecting the envelope in the radial direction using the relation

$$\tau = N_s \pi a^2 Q_{EXT},$$

where Q_{EXT} is the extinction efficiency factor calculated in accordance with Mie's theory. Taking $a = 0.16$ μm, we obtained $Q_{EXT} = 8.7$ for the band V. The weighted mean over all our observations for the reduction in the brightness in the circumstellar envelope is $0^m.8$. Using the dependences between τ_V and ΔV given in Fig. 5, we find $\langle \tau_V \rangle_1 = 1.95$ for the plane geometry and $\langle \tau_V \rangle_2 = 2.35$ for the spherical geometry, and accordingly $N_{S1} = 2.8 \cdot 10^8$ cm^{-2} and $N_{S2} = 3.4 \cdot 10^8$ cm^{-2}.

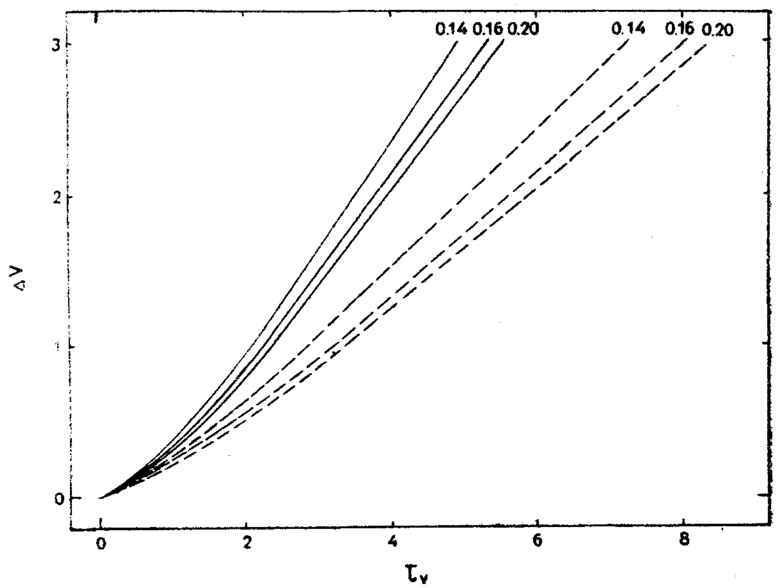

Fig. 5. Theoretical dependences between the fading ΔV and the optical thickness τ_V for an envelope consisting of grains of constant radius *a*. The continuous curves represent planar geometry and the broken curves spherical geometry. The values of *a* (μm) are given next to the curves.

4. Thermal Emission of Circumstellar Dust

In Fig. 6, the points and vertical lines show the energy distribution in the spectrum of WW Vul in the interval from 0.36 to 3.4 μm found using UBVJHKL magnitudes corrected for interstellar extinction. For the UBV bands, only the maximal values of the brightness were taken (the points); for the JHKL bands, the observed limits of the magnitudes, including errors of the observations, were taken. It must be borne in mind that very few measurements have been made in the JHKL bands, and therefore they do not make it possible to determine reliably the maximal and minimal light of the star in this region of the spectrum.

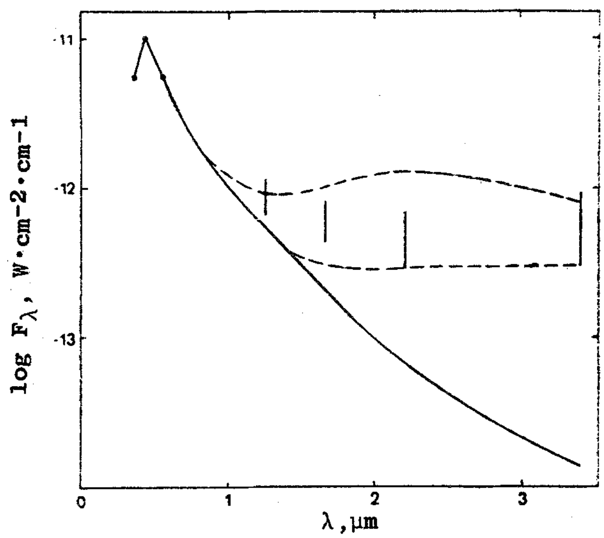

Fig. 6. Spectral energy distributions of WW Vul and a normal star. The continuous curve is the distribution of a normal A2V star; the broken curves are the distributions for a star of the same type but with dust envelope.

For the transition from magnitudes to flux densities at the outer edge of the Earth's atmosphere, the data of [32] were used. The continuous curve shows the spectral energy distribution of a A2V star, for which the UBV magnitudes are equal to the corresponding magnitudes of WW Vul corrected for interstellar extinction. The relative UBVRIJKL magnitudes of the A2V star are taken in accordance with [33]. As can be seen from Fig. 6, the radiation fluxes of WW Vul in the infrared region of the spectrum covered by the JHKL bands is appreciably higher than for a normal star having the same spectral type.

The broken curves in Fig. 6 show the spectral distributions of the thermal emission of the circumstellar dust envelope plus the radiation of a normal A2V star having the same UBV magnitudes as WW Vul. The luminosity of the dust envelope was calculated as

$$L(\lambda) = Q_{\rm ABS}(\lambda)\, 4\pi a^2 \pi B(\lambda,\ T)\, N_\Sigma,$$

where Q_{ABS} is the absorption efficiency factor calculated in accordance with Mie's theory, $B(\lambda, T)$ is the Planck function, T is the temperature of the grains, and N_Σ is the total number of grains. It was assumed that $T = 1000^\circ$K (upper curve) and $T = 800^\circ$K (lower curve), $N_\Sigma = 8 \cdot 10^{36}$, and $a = 0.16$ µm. The number N_Σ was chosen to make the sums of the luminosities $L(\lambda)$ of the star and the envelope correspond to the flux densities $F(\lambda)$ observed at the Earth. In the calculations of Q_{ABS} for the JHKL region the value $k = 0.1$ was taken on the basis of [29] for the imaginary part of the refractive index.

Note that the number N_S defined in the previous section is related to N_Σ by

$$N_S = \frac{N_\Sigma}{\frac{4}{3}\pi (R_2^3 - R_1^3)} (R_2 - R_1) < \frac{N_\Sigma}{4\pi R_1^2},$$

where R_2 and R_1 are the outer and inner radii of the envelope; R_1 can be estimated approximately, since it is the distance at which the temperature of the grains determined by their heating by the emission of the star reaches the value T_e at which their evaporation becomes important. For WW Vul, we take the effective temperature, luminosity, radius, and mass to be the same as for a normal A2V star, i.e., $T_{eff} = 8900^\circ$K, $L_{WW} = 22L_\odot$, $R_{WW} = 2R_\odot$, $M_{WW} = 2M_\odot$. Setting $T_e = 1000^\circ$K (see [24]), we estimate R_1 from the relation

$$\frac{1}{4}\frac{R_{WW}^2}{R_1^2}\int_0^\infty Q_{ABS}(\lambda)\, B(\lambda,\ T_{eff})\, d\lambda = \int_0^\infty Q_{ABS}(\lambda)\, B(\lambda,\ T_e)\, d\lambda.$$

Thus, we obtain $R_1 = 1.5 \cdot 10^{13}$ cm, $N_S < 3 \cdot 10^9$ cm^{-2}.

The estimates of the number of grains deduced from their extinction and from the thermal emission agree to within a factor 10, an indication that there are no gross contradictions in the chosen model of the envelope.

To determine the total mass of the dust and its corresponding matter density $\bar{\rho}$, we take the total number of grains in the range 10^{36}-10^{37}, the density in a grain to be 2 g/cm^3, the radius of the dust envelope to be $1.5 \cdot 10^{13}$ cm, and its thickness $1.5 \cdot 10^{12}$ cm. Hence, $M_\Sigma \approx 10^{22}$-10^{23} g and $\bar{\rho} \approx 10^{-17}$-$10^{-16}$ g/cm^3.

5. Formation and Stability of the Circumstellar Dust Envelope

It is interesting to discuss our estimates when considering the processes that lead to the formation of the envelope and its stability.

a) Formation of Grains in a Gas Envelope Ejected from the Star. Observations of the hydrogen line profiles in the spectrum of WW Vul show that at certain intervals of time the gas moves away from the star with the velocity of order 100 km/sec [23]. It is probable that near the star the ejected gas is heated to a temperature ~10^4°K, and its optical thickness in the ultraviolet of the spectrum is greater than 1. In such a case, the gas absorbs about 30% of the total radiation of the star, and, on the basis of this estimate, we find the change in the gas temperature T from the relation

$$0.3 \cdot 4\pi R^2 \sigma' T^4 = 0.3 L_{WW},$$

where σ' is the Stefan—Boltzmann constant. The decrease in the temperature with increasing R at $T \sim 10^4$°K means that a small change in R already leads to the gas ceasing to be heated by the radiation, since the opacity of the gas decreases with decreasing temperature. Thus, it can be expected that the gas temperature decreases to the value characteristic of H I regions in the interstellar medium, i.e., ~100°K. In addition, at large R we can obtain from the above relation estimates of an upper limit of R for given T: $R \leqslant 1.1 \cdot 10^{13}$ cm for T = 1000°K and $R \leqslant 1.7 \cdot 10^{13}$ cm for T = 800°K.

In accordance with [24], a decrease in the temperature in the range 1000-800°K is one of the necessary conditions of gas condensation into grains. The basic question is the duration of the process of formation of grains with the radius 0.16 μm adopted in our model. According to [24], it is

$$t(a_{max}) = 3.9 \cdot 10^{-2} t_T = 2.8 \cdot 10^4 t_{coll},$$

in which the cooling time scale t_T and the mean interval of time t_{coll} between collisions of monomers are given by

$$t_T = \left| \frac{d \ln T}{dt} \right|^{-1}_{T=T_e}, \qquad t_{coll} = (\alpha_S c_1(0) 4\pi a_0^2 \langle v \rangle)^{-1},$$

where T_e is the equilibrium temperature, and α_S, $c_1(0)$, a_0, $\langle v \rangle$ are the probability of collision, the volume concentration, the radius, and the mean thermal velocity of the monomers. Our estimates of the mass and volume of the circumstellar dust envelope show that the mean density of the dust matter in it is ~10^{17}-10^{-16} g/cm^3, which corresponds to a volume concentration of the gas that condenses into the grains of ~10^9-10^{10} cm^{-3} for hydrogen and ~10^6-10^7 cm^{-3} for the monomers. We can therefore take $t_{coll} \approx 3 \cdot 10^3$-$3 \cdot 10^4$ sec, so that the duration of formation of the grains with a = 0.16 μm is $t(a_{max}) \approx 10^8$-10^9 sec.

We note first that $t(a_{max})$ is much greater than the observed durations of the fadings of the light of WW Vul, which are ~10^6-10^7 sec. Second, the corresponding $t_T \approx 10^9$-10^{10} sec is somewhat greater than but not very different from the duration of cooling of the gas ejected from the star if one assumes that the velocity of the gas decreases to ~1 km/sec at the distance $1.5 \cdot 10^{13}$ cm $\approx 100 R_{WW}$. We mention two acceptable mechanisms of growth of the grains under such conditions. First, growth can occur in individual concentrations in the envelope in which the volume concentration of the gas reaches ~10^{10}-10^{11} cm^{-3} for hydrogen, which corresponds to $t_T \approx 10^8$-10^9 sec and $t(a_{max}) = 10^7$-10^8 sec. Second, the final increase in the radius of the grains to 0.16 μm may be achieved by the grains repassing through a region in which the temperature is fairly low but the gas is not too rarefied. Such a mechanism of grain growth was first proposed by Salpeter [34]. Note that the observations of the Balmer line profiles in the spectrum of WW Vul also indicate that the motions of the gas from the star are replaced by motions toward it [23].

b) The Emission of the Gas Component of the Envelope. Since the mass of the silicate grains formed from the gas is a certain fraction (~1%) of the mass of the gas, it can be assumed that in the parts of the circumstellar envelope in which the dust density is high there is also more gas. So far as is known, in the UBV bands the dust extinction is appreciably higher than the gas extinction, but the gas in the inner part of the envelope, where it is heated to ~10^4°K, may radiate, especially in U and partly in B. It may therefore be assumed that the fadings in the light of the star are accompanied by a relative enhancement of the emission at wavelengths $\lambda \leqslant 4000$ Å, as was observed in [18].

In addition, the connection between the absorption of the dust and the emission of the gas cannot always be the same because of the fact that the weakening in the light of the star is caused mainly by dust projected onto the disk of the star, while the emission of the circumstellar gas is not restricted to this narrow region. Such considerations can explain the deviation of the dependences V, (B − V) and V, (U − B) determined in Sec. 3 for the dust extinction from the observed dependences, and also the irregularities of these dependences noted in Sec. 2.

c) Interstellar Dust Falling Toward the Star. It can be assumed that dust falls toward the star, for example, from the "placenta" nebula from which the star itself was formed by gravitational condensation. The observations do not contradict the assumption that in the considered nebula there are no radial motions with velocities significantly exceeding the velocity of sound except for a region near the surface of the star. Therefore, slow accretion of dust is admissible in our model of the circumstellar envelope, and the change in the temperature of the gas and dust with the distance from the star remains the same as in the case of matter outflow from the star. In particular, there is no change in the estimate of the radius of the region within which grains cannot exist ($R_1 = 1.5\cdot10^{13}$ cm).

d) Stability of the Envelope. The circumstellar envelope can be quasisteady if the individual particles in it rotate about the star in Kepler orbits, the rotation deriving from the axial rotation of the star or the "placenta" nebula. It can be shown that for our model of the envelope the stable existence of individual clouds is then impossible. The obtained density of the gas—dust matter is $\sim10^{-15}$–10^{-14} g/cm^3. On the other hand, for a body with density ρ revolving in a circular Keplerian orbit of radius R around a star with mass M_{WW} an equilibrium configuration is impossible if

$$\rho \leqslant \rho_{CR} = \frac{11\, M_{WW}}{\pi R^3}$$

(Roche criterion, see [35]). In the case of WW Vul $\rho_{CR} = 4\cdot10^{-6}$ g/cm^3 at $R = 1.5\cdot10^{13}$ cm; this density is much greater than the mean density of the gas—dust envelope.

However, the presence in the light curve of deep minima indicates strong inhomogeneity of the dust envelope, this probably being due to hydrodynamic processes taking place in it. It is possible to estimate the size of these inhomogeneities under the assumption that the observed fadings in the light of the star are due to eclipses of it by temporary formations of the dust orbiting the star. In the case of the motion of grains in circular orbits with radius $1.5\cdot10^{13}$ cm, the orbital period is ~0.7 yr or $2\cdot10^7$ sec. The total duration of the fadings with amplitude of about 2^m does not differ strongly from this value. But, as we have seen, there is also observed to be a "fine structure" in the form of lesser fadings that are superimposed on the larger ones and have a duration of ~10^6 sec. Thus, it can be assumed that the largest inhomogeneities have a size of the order of the entire envelope (10^{13} cm) but that there are also inhomogeneities with diameter approximately ten times less (10^{12} cm).

6. Conclusions

It has been established that the fadings in the light of WW Vul have a duration in the range 10^6–10^7 sec, their depth reaching $2^m.2$ in V. The fadings in the UBV bands can be explained by scattering and absorption of light in an inhomogeneous dust envelope consisting of silicate particles of mean radius 0.16 μm and total number 10^{36}–10^{37}. Under the assumption that the grains are heated to 800-1000°K, the observed radiation excess of WW Vul in the range 1.65-3.4 μm can be explained.

There is a certain deviation between the observed dependences between V and the color indices (B — V) and (U — B) and the dependences determined for fadings due solely to variations in the extinction of the circumstellar dust envelope. In addition, the observed dependences exhibit a large spread, i.e., they are not single valued. Both these results may be explained by the fact that reduction in the radiation of the star by dust extinction is not the only cause of the changes in the light of WW Vul. It is probable that in the envelope of WW Vul there is not only dust but also heated gas whose radiation is superimposed on the emission of the star.

It should be noted that the opacity of the grains in the region 0.36-3.4 μm must be assumed to be appreciably greater than for pure silicate grains. Like other authors, we assume that the opacity of the grains is due to their "contamination"; this appears reasonable but must be verified by calculations of grain models. Thus, the proposed model of a circumstellar dust envelope is to a certain degree problematic. We mention that the opacity in the region covered by the UBV bands may be due to the presence in the grains of the oxide SiO, but the origin of the opacity in the region of the JHKL bands is not clear.

Because of the high temperature and luminosity of WW Vul grains can probably exist in its envelope only at distances above ~$100R_{WW}$ ($1.5\cdot10^{13}$ cm). Our estimates of the matter density in the envelope demonstrate the possibility of formation of grains from gas ejected from the star, the velocity of the gas decreasing to ~1 km/sec at a distance of ~$100R_{WW}$. The assumption of slow accretion of grains from the "placenta" nebula also does not contradict the observations. The inhomogeneity of the envelope indicated by the variations in the light of the star is to be regarded as an indication of the formation of transient concentrations in the envelope.

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