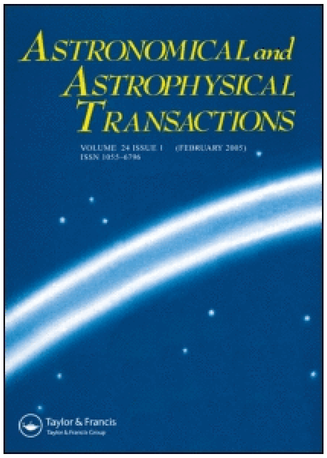

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DUST IN EXPANDING WOLF–RAYET STAR ATMOSPHERES. I. AN ANALYSIS OF INFRARED OBSERVATIONS AND POSSIBLE DYNAMICAL MECHANISM OF THE DUST GRAIN GROWTH

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Infrared observations of some WR stars are interpreted as an indicator of the presence of expanding, inhomogeneous dust envelopes at the distances $\approx 10^5$–$10^6\,R_*$. Physical properties of dust in the WR shells are investigated in detail. It is shown that the dust grain growth in the WR shells is independent of the dust formation mechanism and takes place under the conditions of thermodynamic undersaturation.

KEY WORDS WR stars, infrared radiation, dust physics.

1. INTRODUCTION

Ground-based and IRAS infrared observations revealed considerable IR excess in a large group of WR stars. Undoubtedly, carbon dust is the main source of IR emission in WC8-10 stars. The IR emission of these stars can be partially explained by free–free emission of electrons in the expanding atmosphere. This is a dominant mechanism for early WC and WN stars. Theoretical estimates of the size of the dust formation zone have been made basing on the assumption that the dust absorbs stellar ultraviolet radiation and reemits it in the infrared (Williams *et al.*, 1987). However, we face a serious question: how dust grains form and grow in the severe high-temperature conditions of a WR star atmosphere? In the present work we show that some IR observations provide evidence for the existence of expanding, inhomogeneous dust shells near these stars. Furthermore, we propose a possible mechanism of the dust grain growth in WR star atmospheres: the dust grains grow when colliding with carbon ions. The growth and dynamics of carbon grains in the atmospheres of WR stars is studied basing on this idea.

2. ANALYSIS OF INFRARED OBSERVATIONS

2.1. *The Finite Diaphragm Size and the IR Variability of Some WC Stars*

There are some theoretical estimations of the size of dust formation zones, based on the assumption that the dust absorbs the Wolf-Rayet star ultraviolet flux and reemits it in the infrared. These estimations allow to determine more or less definitely r_0, the inner radius of the dust formation zone. The outer radius is $r_1 \approx (1 \div 1000)r_0$ (Williams *et al.*, 1987). For HD 192641, this yields $r_0 = 6130R_*$. Adopting the value 1.82 kpc for the distance to HD 192641 and $13R_\odot$ for R_*, we have $r_0 = 0.2''$ and $r_1 = 20''$ if $r_1/r_0 = 100$. It should be noted that the value of r_0 strongly depends on the model assumptions. Therefore, r_1 can be close to the size of the field diaphragm commonly used in near-infrared photometry. The value of r_1 will be somewhat larger if the dust is heated by some other agents (shock waves, a close companion, etc.). If the field diaphragm allows to study only some part of the dust shell, one can detect an apparent growth of the infrared flux when the diaphragm size increases. It is increasing to reexamine the results of some observations of WC stars from this point of view.

In 1970–1975, the infrared variability was discovered for HD 192641 (WC7 + abs, $d = 1.82$ kpc), HD 193793 (WC7 + 04 − 5, $d = 1.34$ kpc) and HD 168206 (WC8 + 08 − 9 IV, $d = 2.0$ kpc). The observations have been carried out with one and the same photometer but using the diaphragm of 11″ in 1973 and 7″ in 1975 (Hackwell *et al.*, 1976). In Figure 1 the wavelength dependence of the difference

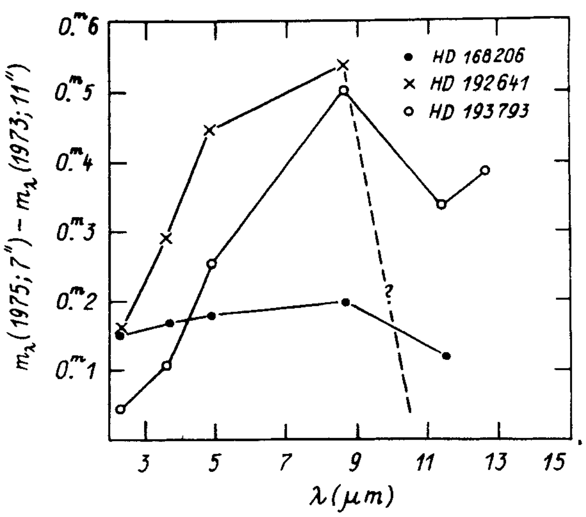

Figure 1 $m_\lambda(1975; 7'')-m_\lambda(1973; 11'')$ as a function of λ.

$[m_\lambda(1975; 7'') - m_\lambda(1973; 11'')]$ is plotted. It is evident from this figure that all three observed WC7-WC8 stars with dust shells demonstrate the same dependence of Δm_λ on the wavelength λ. Hackwell *et al.* (1976) have interpreted this phenomenon as a variability connected with significant mass loss rate variations and recurrent dust shell formation. The other seven WR stars studied by these authors (which have no dust shells) do not show such wavelength dependence of m_λ. Can this variability be caused in part by the difference of the diaphragm size? The total infrared flux of WC stars is produced by a nearly point-like stellar source (stellar radiation + free–free radiation of the wind) and by an extended dust shell. Then, if the diaphragm allows to see only a part of the dust shell, the growth of $m_\lambda(7'')$–$m_\lambda(11'')$ with λ will take place as the shell angular diameter increases with λ and the contribution of the extended dust shell into the total infrared flux increases. For WR 104 (WC9), the speckle-interferometry (Dyck *et al.*, 1984) indicates that $r_0(4.8\,\mu\mathrm{m})/r_0(2.2\,\mu\mathrm{m}) \approx 2.4$.

There exist some interesting tendencies. Firstly, the larger is r_0, the larger is Δm_λ $[r_0 = 6130 R_*$ (HD 192641), $r_0 = 1490 R_*$ (HD 193793), $r_0 = 421 R_*$ (HD 168206 ≡ CV Ser)—Williams *et al.*, 1987]. Secondly, these three stars are binaries and r_0 correlates with the orbital period [P(HD 193793) = 7.9 years (Moffat *et al.*, 1987), P(HD 192641) ≈ (1.5–2) ∗ P(HD 193793), P(HD 168206) = 29.7 days]. Recurrent formation of dust shells in HD 192641 and HD 193793 (Williams *et al.*, 1985, 1990; Hackwell *et al.*, 1979) is connected with the periastron passage of the companion, and the dust heating can take place during the closest approach of the companions (the wind–wind interaction). To estimate the influence of the "diaphragm effect" ("d.e.") we approximated the HD 193793 IR mean light curves (Williams *et al.*, 1990) by

$$I_\lambda(\varphi) = m_\lambda^{\max}/m_\lambda(\varphi) = \sum_{i=1}^{n} \left(\frac{c}{\varphi - \varphi_0}\right)^{\alpha_i}, \tag{1}$$

where $m_\lambda^{\max}$ is the maximal magnitude at a given wavelength λ, $c = 0.009$, φ is the phase, $\varphi_0 = 0.13$ for $\lambda = 8.7$, 11.6, 12.5 μm (Williams *et al.*, 1990), α_i varies within the range 0.09–0.20 for different λ and different light curve segments, and $n = 2$–3.

These calculations show that expected values of $\Delta m_\lambda = m_\lambda(1975)$–$m_\lambda(1973)$ are by $0\overset{m}{.}02$–$0\overset{m}{.}16$ higher than the observed ones. The "d.e." is more pronounced for $\lambda > 5\,\mu$m and reaches a maximum at $\lambda = 8.7\,\mu$m. As a consequence, we can see the net "d.e." probably for HD 168206 as shown in Figure 1, and the sum "d.e." + dust shell formation variability (a dominant Δm_λ source), for HD 192641 and HD 193793.

It would be interesting to reconsider observations of WR112 (CRL 2104, d = 1.2 kpc only!) and WR118 (CRL 2179, $d = 3.70$ kpc) (Roche *et al.*, 1976) from this viewpoint. Can the "diaphragm effect" partly explain the great discrepancies in the IR fluxes measured with different equipment?

2.2. *Probable asymmetry of the dust shells*

The infrared fluxes of 38 WR stars have been measured during the IRAS experiment. It has been found that 24 stars (out of 38) have dust shells. The position accuracy of IRAS observations is sufficiently high, $\bar{\sigma} < 20''$. We processed the point source IRAS catalogue data (Beichmann *et al.*, 1985) using a simple

Table 1

The maximum difference of the coordinates for WR stars with cold dust shells

Star	*Sp*	*Max. diff.*	σ_a
WR 71	WN6	71″	49″
WR 89	WN7	81″	57″
WR 116	WN8	30″	29″
WR 130	WN8	75″	18″
WR 122	WN10	9″	27″
WR 85a	WN11	3″	35″
WR 114	WC5	37″	24″
WR 15	WC6	13″	15″
WR 137	WC7 + abs	40″.5	15″
WR 140	WC7 + 0	6″	29″
WR 53	WC8	12″	33″
WR 70	WC8 + abs	1″.5	25″
WR 113	WC8 + 08	43″.5	21″
WR 73	WC8.5	7″.5	49″
WR 76	WC8.5	6″	19″
WR 96	WC8.5	13″.5	82″
WR 69	WC9	16″.5	29″
WR 80	WC9	12″	43″
WR 103	WC9	16″.5	48″
WR 104	WC9	2″	35″
WR 106	WC9	10″.5	56″
WR 112	WC9	2″	26″
WR 121	WC9	59″	32″
WR 118	WC10	3″	18″

Table 2

The maximum difference between the exact and IRAS coordinates for WR stars without cold dust shells; σ_a is smaller than the maximum difference of coordinates for all the cited stars.

Star	*Sp*	*Max. diff.*
WR 133	WN4.5 + 09Ia	13″.5
WR 6	WN5	0″
WR 139	WN5 + 06	4″.5
WR 134	WN6	4″
WR 136	WN6	0″
WR 78	WN7	0″
WR 16	WN8	9″
WR 40	WN8	7″.5
WR 145	WN(C)	12″
WR 146	WC4	25″
WR 48	WC6 + 09.5I	4″.5
WR 90	WC7	11″
WR 11	WC8 + 09I	11″

criterion: the point source was considered to be connected with the nearest star if the difference between the IRAS and exact stellar coordinates was smaller than 90″. The WR exact coordinates were extracted from those given in the catalogue of van der Hucht *et al.* (1981). The results are presented in Tables 1 and 2. Table 1 contains the data for WR stars having dust shells: the WR star number in the catalogue (van der Hucht *et al.*, 1981), the spectral type, the maximum difference between the exact and IRAS coordinates $\sigma_a = 2.45\ \sigma$, where σ is the major axis of the uncertainty ellipse. In some cases the observed dust emission may not be connected with the WR star. This can be clarified by an individual study of such dust sources with higher angular resolution.

Table 2 presents the same data for WR stars without cold dust. So, the difference between the exact and IRAS coordinates may arise because some WR stars are surrounded by inhomogeneous and extended dust shells.

3. A POSSIBLE DYNAMICAL MECHANISM OF THE DUST GRAIN GROWTH

Williams *et al.* (1987) have studied formation and growth of dust grains in a WR star shell. They analyzed the case of thermodynamic quasiequilibrium and came to the conclusion that dust formation and growth in a WR star shell are impossible in this case. We have investigated physical properties of the dust grains in a WR star shell including their dynamics, growth, electric charge and thermal balance. We found that carbon grains can grow in a WC star shell due to collisions with positive carbon ions inspite of the positive charge of the grains and thermodynamic undersaturation. The growth can be explained by the fact that the dust grains are moving in a WC shell at the drift velocity which exceeds the thermal velocity of carbon ions. However, the nucleation problem still remains obscure.

The aim of this section is to show a principal possibility of the dust growth through ion sticking. We shall consider the cases of both graphite and amorphous carbon dust grains.

3.1. *Basic Equations*

Our calculations show that the thermal balance of dust grains in the WR shell is determined mainly by the absorption of stellar ultraviolet radiation and infrared reemission. At typical distances $R > 10^2$–$10^3 R_*$, the role of collisions is negligible. The dust temperature calculations are based on the thermal balance equation in the form (Spitzer, 1978)

$$\left(\frac{R_*}{R}\right)^2 \bar{Q}(a,\ T_*)\sigma T_*^4 = 4\bar{Q}(a,\ T_d)\sigma T_d^4, \tag{2}$$

where R_* is the stellar radius, R is the distance to the star, $\bar{Q}$ is the mean Planck absorption efficiency of the dust grain, a is the radius of the dust particle, T_* is the stellar effective temperature, T_d is the temperature of the dust particle and σ is the Stefan–Boltzmann constant. The optical parameters of Draine and Lee (1984) for graphite grains and the data of Bussoletti *et al.* (1987) for amorphous carbon grains were used for evaluation of $\bar{Q}$. Eq. (2) is valid when the drift velocity of the grains is small and no dense clouds exist in the wind. Otherwise collisions with ions and atoms heat the dust grains. The dust grain dynamics is dominated by the stellar radiation pressure and dynamical friction force (with the gravitational force being insignificant). We obtain the following approximate equation for the drift velocity (Draine and Salpeter, 1979):

$$\left(\frac{R_*}{R}\right)^2 \bar{Q}(a, T_*)\sigma T_*^4 = cu \sum_k m_k n_k \frac{8}{3\sqrt{\pi}} \left(\frac{9\pi}{64} u^2 + \frac{2kT}{m_k}\right)^{1/2}, \tag{3}$$

where c is the speed of light, T is the plasma temperature, m_k and n_k are the mass and number density of the ions of the type k (summation includes only the matter captured into the dust grains), $\bar{Q}$ is the Planck mean cross-section and u is the drift velocity in the frame associated with the outflowing gas.

The equation of radial motion for a dust grain in the WR star shell is given by

$$\frac{dR}{dt} = v + u, \tag{4}$$

where v is the shell expansion velocity relative to the star. For $R > 10^2$–$10^3 R_*$ we can adopt $v = v_\infty = \text{const}$.

The electric charge equilibrium for the dust particle is determined by the balance of the photoelectric effect (caused by the stellar ultraviolet radiation) and collisions with electrons. We have (Draine and Salpeter, 1977)

$$N_e\left(\frac{8kT_e}{\pi m_e}\right)^{1/2}\left(1 + \frac{eU}{kT_e}\right) = \int_{\nu_0}^{\infty} \frac{J_\nu}{h\nu} Q_\nu y_\nu \, d\nu + J_i. \tag{5}$$

where N_e and T_e are the concentration and temperature of the electron gas , m_e is the electron mass, U is the electric potential of the dust grain, J_ν is the stellar radiation flux, y_ν is the photoelectron yield and J_i is the ion flux. We used for y_ν the expression $y_\nu = y_1(1 - y_2/h\nu)$, where $y_1 = 0.05$ and $y_2 = 7$ eV for graphite (Bel *et al.*, 1989). Equation governing the dust grain growth is adopted, in a modified form, from Draine and Salpeter (1979):

$$\frac{da}{dt} = \Omega\left[\sum_k \left[\frac{n_k^c}{4}\left(u^2 + \frac{8kT}{\pi m_c}\right)^{1/2}\left(1 - \frac{2z_k eU}{m_c u^2}\right)(s_k - y_k)\right] - \frac{p_s(T_d)}{(2\pi m_c k T_d)^{0.5}}\right], \tag{6}$$

where Ω is the elementary volume per atom in the dust grain, n_k^c is the number density of carbon atoms ($k = 0$) or ions ($k > 0$) which carry the charge z_k and the mass m_c, s_k is the sticking probability for atoms or ions, p_s is the saturation pressure for carbon, y_k is the sputtering yield for the ion of the type k. In Eq. (6), it is taken into account that the grains grow due to collisions with supersonic carbon ions (the number density of neutral carbon atoms is considerably smaller than that of ions). The dust evaporation depends on its temperature and on the sputtering effect. The expression in brackets is the efficiency of atom or ion collisions with dust grains with proper allowance for the electric interaction. We used the theory of Draine and Salpeter (1979) to estimate the sputtering yield.

3.2. *Results*

The calculations of the growth and dynamics of dust grains have been made for WR star shell conditions basing on equations (2)–(6) for graphite and amorphous carbon grains. The shell expansion velocity v was adopted to be 2000 km/s; the gas temperature within the shell T, 6000 K; the mass loss rate, $\dot{M} = 8 \cdot 10^{-5} M_{\odot}$/yr; and the stellar radius R_*, $10R_{\odot}$. The assumed chemical composition (by mass) is: C/He = 0.6, O/He = 0.06 (this is typical of late WC stars); the sticking probability s is 1.0 (we supposed that carbon ions are implanted into dust grain with the probability about 1). The stellar effective temperature has been varied in the range $T_* = 20{,}000$–$34{,}000$ K. The ionization state has also been varied although it turned out that the results are only weakly sensitive to such variations. To calculate the relative concentrations of carbon ions, we used the corresponding data of van der Hucht *et al.* (1986). For the adopted effective temperature range, the carbon ions C^{++} prevail (from 80% to 100%). The neutral carbon abundance does not exceed 10^{-8}–10^{-6} relative to the full carbon. It has been adopted that the radius of the condensation nucleus is 0.4 nm.

As the shell expansion velocity v is adopted to be constant, we expect to obtain an inverse square law for all plasma constituents. For the plasma carbon, this law is valid only when the relative amount of carbon in the condensate state (with respect to the full carbon, plasma + condensate) is considerably below unity. The results presented in the next our paper show that this is the case: the mean amount of condensed carbon is 0.01–4%. Thus, the continuity equation for the stellar wind is valid.

The essence of the calculations lies in the following: it is adopted that a condensation nucleus is formed at such a distance from the star where the dust grain growth rate is positive. That is, if a nucleus is formed, then it should grow.

Table 3

The physical parameters of WC star dust shell.

T_* 10^3K	R_o R_*	σ_o *nm*	σ_f *nm*	T_o *K*	u_o *km/s*	u_f *km/s*	α_o	α_f
20	240	0.4	10.0	1863	15.1	75.4	2.4	10.2
	94	0.4	18.1	1934	11.1	74.4	0.9	9.7
22	310	0.4	6.8	1851	19.1	79.1	4.1	11.8
	122	0.4	11.3	1918	14.0	74.6	2.1	11.0
24	390	0.4	4.6	1842	23.8	81.0	5.9	13.2
	154	0.4	7.4	1906	17.4	74.9	3.6	12.2
26	483	0.4	3.2	1834	29.0	82.4	7.8	14.6
	190	0.4	5.0	1897	21.3	75.1	5.3	13.4
28	588	0.4	2.2	1826	35.0	81.4	9.8	15.7
	231	0.4	3.5	1889	25.6	75.3	7.0	14.6
30	709	0.4	1.6	1817	41.5	82.1	11.9	17.0
	277	0.4	2.5	1881	30.4	75.5	8.9	15.7
32	848	0.4	1.2	1805	48.8	85.4	14.0	18.5
	329	0.4	1.8	1874	35.8	75.7	10.8	16.8
34	1030	0.4	0.8	1789	56.8	81.8	16.1	19.2
	387	0.4	1.3	1866	41.6	75.9	12.7	17.9

For each T_*, upper line corresponds to graphite particles and lower one to amorphous carbon particles.

The formed dust grain moves away from the star under stellar radiation pressure and grows.

The main results of model calculations are presented in Table 3, where T_* is the stellar effective temperature in units of 1000 K; R_0 is the inner radius of the dust shell measured in units of the stellar radius; a_0 is the radius of the condensation nucleus in nm; α_f is the final radius of the dust grain size in nm; T_0 is the dust temperature at the distance R_0 in K; $u_0(u_f)$ is the initial (final) drift velocity of dust grains at the distance $R_0(\infty)$ in km/s; $\alpha_0(\alpha_f) = eU/kT_e$ is the initial (final) electric energy of the dust grain at the distance $R_0(\infty)$. It can be seen from Table 3 that the dust grain drift velocities are much higher than the ion thermal velocities (3–4 km/s) and may reach 70–80 km/s; the typical dust grain temperatures at the inner shell radius are 1800–1900 K.

Finally, it can be concluded from Eq. (2) and Table 3 that the dust, which is responsible for the WC star IR excesses (Williams *et al.*, 1987), has the mean temperature in the range 1800–1900 K and is located at the distance $\approx 10^3 R_*$. According to our calculations, the dust at the distances 10^5–$10^6 R_*$ has the temperature about 100 K. Therefore, the observed hot ($T_d = 1000$ K) dust shells at the distances 10^5–$10^6 R_*$ (the "diaphragm effect") possibly indicate the presence of dense clouds in the winds of WR stars at such large distances from the star. This can cause dust-gas heating by the probable shock waves arising due to the difference of the cloud and stellar wind velocities.

4. CONCLUSIONS

In the present work it has been shown that the data of some WR stars indicate the existence of expanding, inhomogeneous dust shells at the distances 10^5–$10^6 R_*$. The following experiments can be proposed to study the volume dust distribution near WR stars. The first experiment is the registration of the infrared flux in the range $\lambda > 5\ \mu$m with the diaphragm set 5″–30″. And the second experiment is the mapping of a WR star neighbourhood (the field $2' \times 2'$) in the range $\lambda > 12\ \mu$m (to search for far-infrared sources).

To account for the WR star infrared excess and IRAS data, the dust nucleation and growth have to be understood. In this respect, we have shown that the principal possibilities for the carbon dust grain growth exist in the WR star shell independently of the dust formation mechanism. The dust growth can take place under the conditions of thermodynamic undersaturation by means of implantation of impinging carbon ions into the dust particles. The dust grain drift velocity approaches high values. The possible presence of dense clouds in the winds of WR stars should cause some heating of dust grains at large distances from the star. The presence of dense clouds seems to be a necessary condition for dust nucleation and formation as well. We shall analyze these questions in more detail in our subsequent papers.

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