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**НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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DYNAMICS OF DUST GRAIN IN THE SUBLIMATION ZONE OF COLD WHITE DWARFS

Abstract. The dynamics of evaporating silicate and graphite dust grains moving in circular and parabolic orbits near the cold white dwarf WD J1644-0449 with $T_{eff} \approx 3830K$ is calculated. The rate of sublimation is given by the heating temperature of dust grains depending on the distance to the star, the material parameters, and the radius of dust grains considered in the range from 0.01 to 100 µm. It also took into account the influence of radiation pressure and the Poynting-Robertson's drag on dust dynamics. According to our calculations, all considered sizes of silicate dust grains, leaving the parent bodies on circular orbits completely evaporate at a distance of about 3 stellar radii from the star. The boundary of the dust-free zone (graphite grains) is located twice closer to the star, i.e. at a distance of about 1.5 stellar radii and it is confidently expressed only for larger grains with radius s > 0.5 µm. Our calculations have shown that both silicate and carbonaceous grains can fall on a cold white dwarf directly without reaching complete evaporation if the parent bodies and dust particles move in elongated orbits close to parabolic. The enrichment of the stellar surface with heavy elements can occur without the observed presence of dust in the stellar's vicinity.

Key words: white dwarf, debris disk, sublimation (evaporation), dynamics of dust grains.

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СУЫҚ АҚ ЕРГЕЖЕЙЛІ ЖҰЛДЫЗДАРДЫҢ СУБЛИМАЦИЯ АЙМАҒЫНДАҒЫ ТОЗАҢДЫ БӨЛШЕКТЕРІНІҢ ДИНАМИКАСЫ

Аннотация. Эффективті температурасы $T_{eff} \approx 3830K$ болатын WD J1644–0449 суық ақ ергежейлі жұлдыздың маңайындағы буланатын силикат және графит тозаңды бөлшектерінің дөңгелек және параболалық орбиталары бойынша динамикасы есептелді. Сублимация қарқыны тозаңды бөлшектердің жұлдыздан ара қашықтығына тәуелді, материал типіне және 0.01 мкм мен 100 мкм аралығындағы тозаңды бөлшектің өлшеміне тәуелді болатын олардың қызу температурасы арқылы беріледі. Тозаңның динамикасына сәуле шығару қысымының және Пойнтинг-Роберт эффектісінің әсері ескерілді. Біздің есептеулеріміз бойынша ғарыштық денені дөңгелек орбитамен тастап шығатын барлық қарастырылған өлшемдегі силикаттық тозаңды бөлшектер жұлдыздан үш жұлдыздық радиуста толық буланады. Графит тозаңды бөлшектерінің тозаңсыз шекара аймағы жұлдызға екі есе, яғни шамамен 1.5 жұлдыз радиусы қашықтығында орналасады және радиусы s > 0.5 мкм болатын үлкен бөлшектер үшін анық байқалады. Біздің есептеулеріміз егер ғарыштық денелер және тозаңды бөлшектер параболалық орбитаға ұқсас орбитамен қозғалатын силикат және графит тозаңды бөлшектерінің толық ерімей, суық ақ ерегежейлінің бетіне тікелей түсуі мүмкін екендігін көрсетеді. Жұлдыз бетінің ауыр элементтермен толықтырылуы жұлдыздың маңындағы тозаңды бөлшектердің байқалмайтын көріністерінсіз жүруі мүмкін.

Түйін сөздер: ақ ергежейлі жұлдыздар, тозаңды диск, сублимация (булану), тозаңды бөлшектер динамикасы.

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ДИНАМИКА ПЫЛЕВЫХ ЧАСТИЦ В ЗОНЕ СУБЛИМАЦИИ ХОЛОДНЫХ БЕЛЫХ КАРЛИКОВ

Аннотация. Проведены расчеты динамики испаряющихся силикатных и графитовых пылевых частиц около холодного белого карлика WD J1644–0449 с $T_{eff}\approx$ 3830K при движении по круговым и параболическим орбитам. Темп сублимации задается температурой нагрева пылевых частиц в зависимости от расстояния до звезды, параметров материала и радиусов пылинок, заданных в пределах от 0.01 до 100 мкм. Учитывалось влияние давления радиации и эффекта торможения Пойнтинга-Робертсона на динамику пыли. Согласно нашим расчётам, силикатная пыль всех рассмотренных размеров, покидающая родительские тела с круговых орбит, полностью испаряется на расстоянии около 3 звёздных радиусов от звезды. Граница беспылевой зоны графитовых частиц находится вдвое ближе к звезде, то есть на расстоянии около 1.5 радиусов звезды и уверенно выражена только для более крупных частиц радиусами s> 0.5 мкм. Наши расчёты показали, что пыль как силикатной, так и карбоновой природы может попадать на холодный белый карлик непосредственно, не достигнув полного испарения, если родительские тела и частицы пыли движутся по вытянутым орбитам, близким к параболическим. Обогащение поверхности звезды тяжёлыми элементами может происходить без наблюдаемых проявлений присутствия пыли в окрестности звезды.

Ключевые слова: белый карлик, диск осколков, сублимация (испарение), динамика пылевых частиц.

Introduction. About 90% of the discovered exoplanets are detected around the stars that eventually will finish their evolution as a white dwarf (WD) including our Sun. Veras [19] considered the evolution of the Galactic stars and showed that the evolution's final stage of most stars with masses from 0.07 to 5-12 Solar masses is WD. The range of this masses composed 95% to 97% of all stars in the Galaxy. Stars of these masses, after passing the red giant stage, lose most of their mass. However, when studying the chemical composition of WD atmospheres, it turned out that about 25% - 50% of WD reveal the presence of metal line in their spectra [20], which corresponds to estimates of planetary systems for Main-sequence stars in the Galaxy [4]. This fact and also the results of infrared (IR) observations show an excess of IR radiation and the presence of silicate spectrallines. This is interpreted by most researchers as an indicator of dust active accretion from asteroids or comets [12].

The analysis of the catalog of 73221 white dwarfs, located in the region of the nearest 100 ps, selected from the data of the recently published catalog Gaia-DR2 [8] shows that the population of white dwarfs dominated by cold objects with T_{eff}<8000 K.

Despite the fact that the luminosity of the WD is constantly decreasing, Fossati et al. [6] argue that during the cooling of the WD from a temperature of 6000 K to 4000 K, hypothetically, a terrestrial planet at a distance of about 0.01 AU from the WD may exist in the habitable zone for about 8 billion years, which is quite enoughfor the possibility of theemergence of complex life forms on it [19,11]. Perets [11] mentionsthat second-generation planets can form in habitability zones that were available for for first-generation stars.

Unfortunately, there are very few direct observations of planets or asteroid-comet matter near white dwarfs using the transit technique.One such object is WD1145+017, discovered by the Kepler (K2) mission [18]. It shows transit passing with a depth of up to 20% and a period of 4.5 hours. This, presumably, debris disk near WD1145+017 is located near the sublimation zone, where the process of active dust evaporation undergoes. Vanderbosch et al. [17] reported the discovery, as part of research under the Zwicky Transient Facility program, yet another WD with transit outside the Roche zone with the period of 107.2 days, which is much longer than the orbital periods in WD1145+017.

In the last decade, significant progress has happened in the study of exoplanet systems thanks to projects such as CoRot, Kepler, GAIA, and TESS. Many planets have been discovered around both Main-sequence stars (MS) and around some evolved stars. In particular, the catalog of Gaia Data Release 2 (DR2) [8] contains several thousand WD candidates.

Hollands et al. [7] reported 524 WD showing spectral lines of heavy elements in their spectra by analyzing objects within 40 pc observed by the GAIA mission. The four coldest WDs with T_{eff}<5000 K have lithium absorption lines. This element disappears in the early stages of stellar evolution as a result of thermonuclear burning. The presence of lithium in the WD atmosphere is clear evidence of the accretion of asteroid-cometary matter [9].

Our study aims to simulate the orbital evolution of dust grains constituent of the outer dust cloud and the subsequent accretion of this matter onto the stellar surface, resulting in enrichment of the stellar atmosphere by heavy elements - metals.

To achieve this goal, we chose a cold WD with clues of the presence of an external material: Gaia DR2 4353607450860305024 (WD J164417.01–044947.7, hereinafter WD J1644–0449) with a temperature of T_{eff} = 3830K.

There is not much information about the WD J1644–0449 yet. Kaiser et al. (2020) [9] provide some data on this dwarf, reporting the detection of Li, Na, K, and Ca in its atmosphere. The authors explain the presence of metals by accretion of the planetesimal. Using model atmospheres, the authors determined the abundance of these elements, and, except for Li, their estimates are consistent with meteorite abundance in the Solar System.

In this paper, we use data and methods developed when studying the dust component in the sublimation region of the Solar System and WD1145+017 [13-15].

Materials and methods. The dynamics of dust grains taking into account evaporation is a class of problems related to the dynamics of bodies with variable mass. The ratio of forces acting on the particle is constantly changing. During the calculation, the sublimation rate is determined depending on the temperature of the grains. The temperature of the grains depends on their size, the constituent material, and the distance to the star. Two types of materials that are present in the interstellar medium are selected: silicate and graphite. Of the silicate materials, we chose basalt as the most satisfying to results of observation of the sublimation region near the Sun [13, 14]. The justification for the choice of this material is given in Shestakova et al. [15].

It is assumed that the dust grains are spherical, have a homogeneous composition and isothermal, sublimate isotropically, and there is no reactive force acting on them. In addition, we ignore the gravitational influence by other small bodies, collisions between grains and consider the grains to be electrically neutral. Calculations were performed for the grains sizes (s) from 0.01 μm to 100 μm.

The parameters characterizing the interaction of stellar radiation with grains are calculated using the Mie theory [2]. When calculating using Mie theory, we utilize the effective factors of absorption (Q_{abs}) and radiative pressure (Q_{pre}). We assume Plank energy distribution in the spectrum of the star. For the values of complex refractive index: m(λ)=n(λ)+ik(λ) for basalt and graphite, we use the results of the laboratory experiments according to [10,5]. We used tables of complex refractive index for the wavelength range from λ_1 = 0.0075 μm to λ_2 = 50 μm in increments of 0.001 μm, with the addition of extrapolated values for the UV range.

The parameters of basalt and graphite, as well as the constant parameters for calculating the sublimation of grains, are given in Table 1. To study the orbital evolution of dust grains, we selected the cold dwarf WD J1644-0449. According to [9], the temperature is T_{eff} = 3830K, M_{star} = 0.45 M_{sun}, and R_{star} = 0.013 R_{sun}. This star shows the presence of spectral lines of lithium and other alkali metals in its spectrum, which is indicators of accretion of the surrounding material onto the stellar surface.

Algorithm for calculating orbital evolution. Taking into account the main forces acting on the dust particle with mass m, we can write the equation of motion in the following form:

$$m\ddot{\vec{r}} = -F_g\vec{e}_r + F_r\left[(1-\frac{\dot{r}}{c})\vec{e}_r - \frac{\vec{v}_r}{c}\right] + F_w\frac{\vec{v}_w - \vec{v}_k}{\left|\vec{v}_w - \vec{v}_k\right|}, \qquad (1)$$

where F_g is the gravitational force, F_r is the radiation pressure, F_w is the stellar wind pressure; c, $\vec{v}_k, \vec{v}_w$ is the speed of light, the speed of the dust orbital motion, and the stellar wind speed, respectively. The second term in equation (1) is the same as in [3], the third term is taken from [1].

To consider the motion of dust grains near white dwarfs, we neglect the influence of the stellar wind. For numerical calculations, it is convenient to decompose equation (1) into two coordinates corresponding to the radial and tangential direction of motion. For numerical calculations of the orbital evolution of the grains, we use a system of three differential equations, where the third one is equation, defining the particle's evaporation rate ds/dt:

$$\frac{d^2r}{dt^2}=r\left(\frac{d\varphi}{dt}\right)^2-\frac{\mu_s}{r^2}\left(1-\beta\right)$$

$$\frac{d^2\varphi}{dt^2}=-\frac{1}{r^2}\left[2r\frac{dr}{dt}\frac{d\varphi}{dt}+\alpha\frac{d\varphi}{dt}\left(1+\frac{R_{star}^2}{2r^2}\right)\right], \quad (2)$$

$$\frac{ds}{dt}=\frac{0.0408}{\delta}P\sqrt{\frac{\mu}{T_d}}, \text{ см/сек.}$$

To calculate the saturated vapor pressure P, on which ds/dt depends, we use the relation $\lg(P) = C_2 - C_3/T_d$, with the coefficients C_2 and C_3 from Table 1, where P is given in Torr. We have adopted the following notations: r – distance to the star; φ – polar angle (the angle of rotation of the vector $\vec{r}$); R_{star} is the radius of the star; $\alpha=\beta\mu_s/c$; $\beta = F_r/F_g$; $\mu_s = GM_{star}$ – gravitational parameter of the stars, G – gravitational constant, M_{star} is the mass of the star, c is the speed of light, μ_s and T_d - molecular weight of the dust particle material and its temperature.

The set of equations (2) are equivalent to a system of five first-order differential equations for the required parameters as functions of time: The initial conditions provided by aseparate file containing data from Table 1: δ , μ, H_L, T_0, and many other data, including material type, star mass and radius, initial grain's sizes, initial distance, radial, and tangential velocity,and other parameters.

Table 1 - Properties of dust materials used in calculations

Material	δ g/cm^3	μ	H erg/g	P_m dyn/cm^2	T_0 K	H_L, 10^{-20} J/ mol	S_2 (T_0,H_L)	$C_3(H_L)$
basalt	2.7	67.0	7. 12e10	1. 07e14	2284	79.2	10.915	24928.3
graphite	1.95	12.0	7. 27e11	4. 31e16	3373	144.9	13.5129	45579.12

The calculations are carried out for particles that break off from their parent bodies with a circular or parabolic orbital velocity and then move independently.

For calculations based on the basic system of equations (2), the values of the light pressure β and the temperature of the particles T_d play an important role. Since the grains are small, the interaction of electromagnetic waves with small particles with a characteristic scale comparable to the wavelength is described by the Mie theory. All calculations were carried out according to computer code compiled according to [2].

The results of calculations based on the theory of Mie depend only on the properties of the material and particle sizes and do not depend on the parameters of the star. Effective absorption factors Q_{abs} are used to calculate the thermal balance of particles, and factors Q_{pre} are used to calculate the light pressure. The Q_{abs} factors for basalt and graphite are given in the form as shown in figures in the previous work [16].

The dust particle temperatures obtained from heat balance calculations are accompanied for comparison by similar calculations for an absolutely black body, which is easily obtained from expression $E_{abs} = E_{rad} + E_{evap}$, assuming: $E_{evap} = 0$ and $\langle Q_{abs}\rangle = \langle Q_{rad}\rangle = 1$.Then a simple relation for the blackbody temperature of the dust is obtained: $T_d = T_{star} (R_{star}/2r)^{1/2}$.

Fig.1 shows the temperature distribution of basalt particles with distance from the star. As can be seen from Fig. 1, that the temperatures of grains with radius less than 100 microns are lower than blackbody temperatures at all distances from $1R_{star}$ to $200R_{star}$; the temperature of particle decreases only within the zone $< 2R_{star}$.

Similar calculations performed for graphite particles showed slightly different results. Unlike the basalt particles, temperatures of submicron graphite particles (Figure 2) are higher than the blackbody temperatures for all distances from the star, even in the immediate vicinity at a distance of $1R_{star}$. The temperature of micron size and larger graphite particles (Figure 2) is similar to the blackbody temperature, except for the innermost zone, located closer than $1.5R_{star}$.

The ratio of the radiation pressure force to the gravitational force $\beta = F_r/F_g$ does not depend on the distance to the star and can be computed as follow:

$$Q_{pr}(s,m)=\frac{\int_{\lambda_1}^{\lambda_2} Q_{pre}(\lambda,s,m)B_{star}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} B_{star}(\lambda)d\lambda},\ \beta(s,m)=\frac{F_r}{F_g}=\frac{3Q_{pr}(s,m)\mathrm{R}_{star}^2\sigma T_{star}^4}{4c\mu_s\delta s}, \tag{3}$$

where $Q_{pre}(\lambda,s,m)$ is the effective spectral factor of radiation pressure, calculated using the Mie theory.

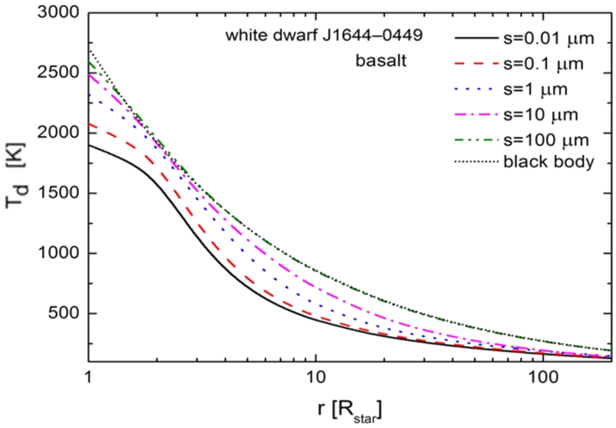

Figure 1. Temperature of basalt particles of different radii as a function of the distance to the star, given in star radius with T_{eff} = 3830K.

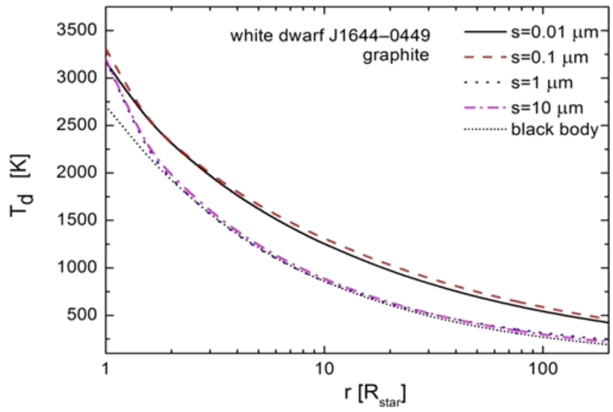

Figure 2. Temperature of graphite particles with different radii depending on the distance to a star with T_{eff} = 3830K.

Figure 3 shows that graphite grains are more susceptible to radiation pressure, and the maximum of its influence falls on grains of submicron sizes.

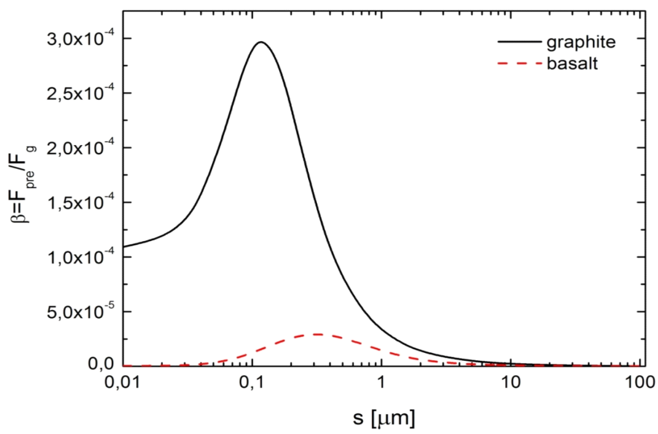

Figure 3. The ratio of radiation pressure to the gravity force depending on the radius of basalt and graphite grains.

Results and discussion. Calculations of the orbital evolution of dust grains in the sublimation region of the white dwarf WD J1644–0449, where the particles are subject to active evaporation, were carried out using the algorithm presented above. There is not much information about this cold ($T_{eff} \approx$ 3830K) white dwarf yet. The presence of dust has not been detected yet, but alkali metals, including lithium, have been reported by Kaiser et al. (2020) [9].

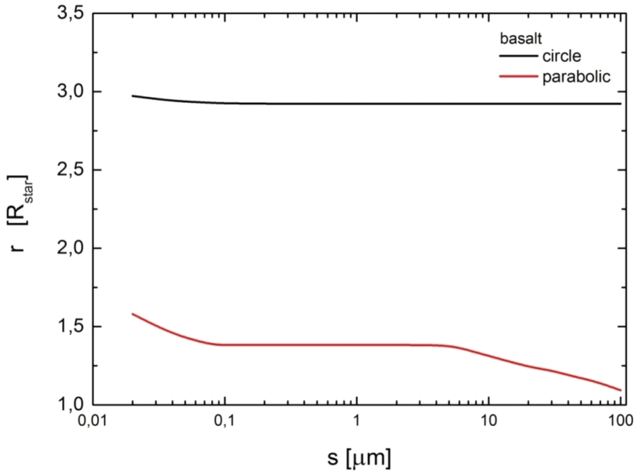

Figure 4. Distances from the star to the inner boundaries of the sublimation region of basalt grains freely moving along circular and parabolic orbits (red line – parabolic, black line - circular).

Figures 4 and 5 shows the results of orbital evolution calculations for basalt and graphite grains moving in circular and parabolic orbits. Grains evaporation occurs very close to the star. Basalt grains moving along circular orbits evaporate at a distance of about 2.9 Rstar, regardless of their initial size (Fig. 4). Large micron grains with radius s > 100 µm, moving along elongated orbits close to parabolic one, dive onto the star long before they completely evaporate (Figure 4).

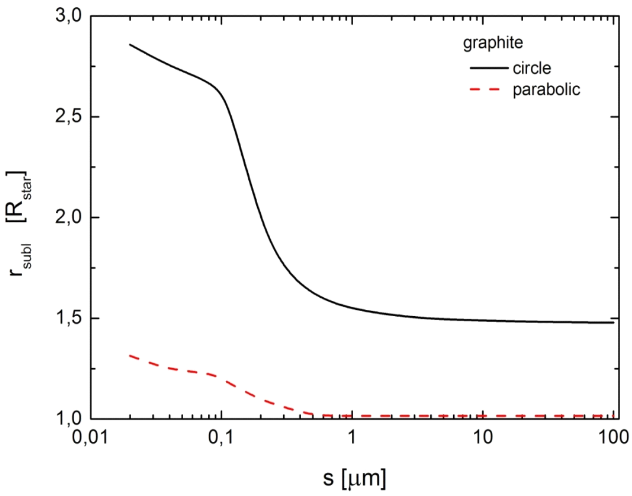

Figure 5. Distances from the star to the inner boundaries of the sublimation region of graphite grains freely moving along circular and parabolic orbits (red line – parabolic orbit, black line -circular orbit).

This property is even more profound for grains shown in Fig. 5. When moving in circular orbits, small grains with radius s < 0.1 µm evaporate in the region close to the evaporation boundary of basalt grains, while larger grains with radius s > 0.5 µm form the evaporation boundary at a distance of about $1.5R_{star}$. Grains of sizes s > 0.3 µm moving on parabolic orbits dive onto the star before completely evaporating.

Conclusions. Our calculations have shown that:

Firstly, dust leaving the parent bodies moving along circular orbits can form a clear boundary of the dust free zone at some distances from the star upon reaching the sublimation region. This distance for basalt grains is about $2.9R_{star}$, corresponding to a blackbody temperature of about T_{bb}=1600K. For graphite grains, this distance is about $1.5R_{star}$, which corresponds to a higher temperature of T_{bb}= 2200K.

Secondly, dust of both silicate and carbon nature can fall on a cold white dwarf directly, without reaching complete evaporation, if the parent bodies and dust particles move in elongated orbits close to parabolic.

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