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LUMINESCENT RECOIL OF THE COSMIC DUST GRAINS

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ABSTRACT

Cosmic dust particles of micrometer and nanometer sizes can luminesce in the optical range of the spectrum under the influence of electromagnetic radiation and electron and proton fluxes. We have suggested that the luminescence of cosmic dust particles may have impact on the spatial position of these small particles. We have shown that the time–constant process of absorption of UV photons by a cosmic crystalline dust particles followed by the re-emission of luminescent photons, will cause the movement of such particles of dust in the opposite direction - luminescent thrust. In the spatial system the star – small particle – ground-based observer, where star, small particle and observer are located on one and the same straight line, the luminescent recoil can lead to its distancing from the star. For the case of diamond nano-dust particles of various sizes, we calculated the velocities of their movement taking into account the contribution of the luminescent recoil. The results of calculations are provided. For variously dispersed crystalline dust particles of different chemical and mineralogical composition, we have considered also various aspects and patterns of their interaction with external factors and forces in the context of the phenomenon of luminescent recoil. In fact, we have shown that in addition to light pressure, the movement of cosmic dust particles can also be caused by the phenomenon of luminescent recoil.

Key words: radiation mechanisms: non - Thermal - (ISM:) solar system – dust - extinction

1 INTRODUCTION

Here we will define the solid cosmic matter segment and the conditions that will be considered. Thus, in this work, we will consider: 1) dust particles of micrometer and nanometer sizes; 2) micro- and nanometer dust located far from strong gravitational fields (stars and planets); 3) the rectilinear motion of micro- and nanometer dust particles; 4) cold crystalline micro- and nanometer dust whose temperature is an order of magnitude lower than that of millimeter dust particles orbiting in the gravitational fields of stars and planets; 5) only the short-wavelength spectrum will be taken into account as the exciting electromagnetic radiation $\Delta\lambda \leqslant 390\,\text{nm}$.

Only the case where the re-emitted light is non-equilibrium, non-thermal radiation will be considered. We will need to keep in mind that photoluminescent radiation from solids is non-equilibrium, incoherent radiation, and does not represent any type of scattering.

The space environment is the interplanetary and interstellar medium characterized by the presence of variously dispersed dust matter. This dust matter forms cloud structures, compact or extended complexes of dust particles with a characteristic chemical and mineralogical composition. The range of sizes of individual dust particles covers significant intervals of their diameters (cross sections), from millimeter to nanometer dust particles.

Micrometer and nanometer dust particles irregularly fill interplanetary and interstellar spaces, being influenced by external forces (gravity, electromagnetic and corpuscular radiation) and processes, including collisions of dust particles with each other. Cosmic dust has a diverse chemical and mineralogical composition; however, it can be divided into three main classes: silicate, organic, and metallic dust. The composition of the substance of individual dust particles determines, to no small extent, the evolutionary path of these nano-, micro- and macro- formations. Ground-based registration, detection of cosmic dust matter can be carried out using spatial features of the distribution of this dust matter. The phenomena occurring in the system: the light source (star) – dust – Ground-based observer, provide us with information about the physicochemical properties of dust particles. Under these phenomena we mean: absorption, emission, scattering, and polarization of light by the dust matter. Individual dust

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grains can be characterized by different internal structure and shape, including homogeneous spheroids; the core - mantle spheroids; asymmetric grains and, etc. Cosmic dust plays a significant role in the evolution of the planetary systems and nebulae. In addition, it is the arrays and cloud formations of micrometer and nanometer dusts that are the main element of the space 'laboratory', which is a spatial system: Star – Dust – Ground based observer. That is why the cosmic dust is an object of a close attention within the interests of astrophysics, space physics and astrochemistry. It seems to us that one more phenomenon can carry significant information about the nature of cosmic dust. This is the phenomenon of luminescence of cosmic dust particles excited by electromagnetic and corpuscular radiation of stars. Cosmic dust particles of micro and nano-sizes can luminesce in the optical range of the spectrum, under the influence of hard electromagnetic radiation and fast electron and proton fluxes from the sun and stars. We put forward the supposition that the luminescence of cosmic dust particles can have a significant effect on the spatial position of these small particles and on some of their dynamic properties. The present work is devoted to the consideration of our supposition.

2 LUMINESCENCE OF SMALL COSMIC DUST PARTICLES

Cosmic dust particles are constantly exposed to hard electromagnetic radiation and fluxes of fast charged particles, namely the effects of X-ray and ultraviolet radiation, as well as fluxes of high-energy electrons and protons of the solar (stellar) wind.

In clouds of particles, if the sizes of these particles are comparable to the wavelength of incoming hard electromagnetic radiation, scattering and diffraction phenomena can occur on small particles of this short-wavelength radiation. In the case of particles significantly larger than the wavelength, the phenomenon of absorption of incoming hard electromagnetic radiation may occur.

We believe that, in addition to the optical consequences of such absorption processes, there may also be dynamic consequences leading to changes in the spatial positions of the particles. The short-wavelength electromagnetic radiation absorbed by the substance of a particle can cause photoluminescence of that particle with different afterglow periods ($\Delta t = 0$ for fluorescence; $\Delta t > 0$ for phosphorescence).

At the same time, photoluminescent emissions of particles will have a longer wavelength than that of the exciting radiation, which may belong to the ultraviolet range of the spectrum. The characteristics of photoluminescent emissions of a specific particle depend on its chemical and mineralogical composition, temperature, and the state of the substance (crystalline or amorphous).

For the majority of particles of silicate or organic composition, at temperatures $T < 273\,\mathrm{K}$ and in the crystalline state of the substance, it is possible to expect the appearance in the optical range of the spectrum of two or more photoluminescent bands with maxima in the vicinity of $\lambda \approx 440$ and $\lambda_1 \approx 730\,\mathrm{nm}$.

In fact, X-ray or ultraviolet radiation of the interstellar medium can cause blue and red photoluminescent glow of dust particles.

The physical features of photoluminescence of micrometer and nanometer mineral dust particles were studied under laboratory conditions, demonstrating characteristic blue and red emissions in the luminescence spectra. In particular, grains of meteoritic forsterite and diamond were considered (Gucsik et al. 2012, 2013; Gaft et al. 2005; Gorobetz & Rogozhin 2001). Figure 1 shows the photoluminescence spectrum of diamond.

Bombardment of dust particles by fluxes of fast electrons and protons causes the phenomenon of cathodoluminescence of the substance of these dust particles. In this case, the characteristics of cathodoluminescent emissions of a specific particle will depend on its chemical and mineralogical composition, temperature, and the state of the substance.

In general, the processes of photoluminescence and cathodoluminescence of solid crystalline substances are similar, differing mainly only in the method of supplying the exciting energy. In our case, photoluminescence of particles can be caused by solar (stellar) hard electromagnetic radiation, while cathodoluminescence of particles can be caused by fluxes of high-energy electrons and protons of the solar (stellar) wind.

In both cases, the dust particle will re-emit the absorbed energy in the optical range of the spectrum in the form of one or more luminescent emissions. The phenomena of cathodoluminescence of dust particles, taking into account the corresponding interstellar conditions, will also be characterized by a certain period of afterglow.

The physical peculiarities and characteristics of cathodoluminescence of micrometer and nanometer mineral particles were studied under laboratory conditions, which demonstrated characteristic blue and red emissions in the luminescence spectra.

In particular, grains of meteoritic forsterite and diamond were considered (Gorobetz & Rogozhin 2001; Gucsik et al. 2012, 2013). Figure 2 shows the cathodoluminescence spectrum of forsterite. In this case also, two bands are observed in the cathodoluminescence spectrum of the Forsterite grains exhibit luminescent features with maxima near $\lambda \approx 490$ and $\lambda_1 \approx 730\,\mathrm{nm}$. This indicates that fluxes of fast electrons of the solar (stellar) wind can induce blue and red cathodoluminescent glow in small particles.

A change in the temperature of the substance of a small particle, or its enrichment with impurities in the form of various ions, can lead to variations in the spectral positions and emission profiles associated with photoluminescence and cathodoluminescence spectra of this particle. The prolonged presence of silicate and diamond particles in the field of action of the solar wind can lead to their chemical enrichment with various ions. At the same time, there may be an adsorption process with the formation of a dust particle mantle, or a process of volumetric absorption of ions by substance of a particle with subsequent localization of ions in the vacancies of the crystal lattice – ion implantation. Ground-based registration of the luminescent glow of interstellar dust particles (variously dispersed cosmic dust) is a specific instrumental task that is not considered here.

3 MOVEMENT OF SMALL DUST PARTICLES CAUSED BY LUMINESCENT PHOTONS

In the space environment, dust particles are exposed to gravitational fields as well as electromagnetic and corpuscular radiation. A dust particle is subjected to the full spectrum of electromagnetic radiation and charged particles with a wide range of energies originating from the illuminating star.

We are interested in the dynamic consequences of the interaction between radiation and a dust particle, specifically the absorption of energy by the particle's substance, followed by the re-emission of part of the absorbed energy. It should be noted that theoretical models describing the motion of small cosmic dust particles in strong gravitational and electromagnetic fields often treat these particles as spherically symmetric, homogeneous bodies with properties similar to those of a black body (Poynting 1903, 1904; Robertson 1937; Mann, Meyer-Vernet & Czechowski 2014; Meyer-Vernet et al. 2015; Czechowski & Mann 2018; Stamm et al. 2019).

Crystalline cosmic dust particles of micrometer and nanometer sizes possess well-defined physical properties; however, they often exhibit irregular shapes and complex chemical and mineralogical compositions. Metallic, silicate, and organic small particles are characterized by specific mechanical, optical, and electrical properties.

These characteristics determine the nature of the interaction between incoming radiation and the particle material. Dust particles reflect part of the incoming energy (e.g. photons in the optical range) while absorbing another part (ultraviolet photons), depending on the spectral position of the absorption bands of the crystalline substance.

The widths and profiles of the absorption bands, as well as their spectral positions, depend, among other factors, on the chemical and mineralogical composition of the particle and its temperature. A cosmic dust particle can be considered as a microparticle or nanoparticle, the substance of which may be in either crystalline or amorphous states. In this study, we consider only small crystalline particles.

Considering the above, and taking into account the optical anisotropy of the material of a small particle, it can be expected that the re-emitted energy (luminescent radiation) will be emitted in specific directions, depending on the location of the corresponding conduction bands in the crystal and the spatial orientation of luminescence centers.

Taking into account the size range of a small particle, we can expect the presence of only a few luminescence centers localized within the particle. In fact, a real cosmic dust particle can simultaneously reflect optical photons in the direction of the illuminating star, absorb ultraviolet photons, and re-emit the absorbed energy in the form of luminescence photons in the opposite or other directions (depending on the optical anisotropy of the crystalline substance of the particle).

Let us consider spherically symmetric crystalline particles. A silicate or diamond particle will have a characteristic absorption spectrum. If a small particle does not absorb radiation in the optical range of the spectrum ($\Delta\lambda = 400$–$800\,\mathrm{nm}$) but has an absorption band in the ultraviolet range ($< 390\,\mathrm{nm}$), then optical photons incident on the particle will be reflected, scattered (elastic collision), whereas ultraviolet photons will be absorbed, followed by subsequent processing of the absorbed energy.

Excluding non-radiative processes, it can be expected that a small particle will release the acquired excess energy in the form of optical radiation, i.e. it will emit a luminescent photon into the environment. This luminescent radiation will be characterized by a longer wavelength relative to the absorbed radiation.

Taking into account all macroscopic aspects of this phenomenon, as well as the relative constancy in time of the external radiation source (stars), it can be expected that a particle will simultaneously and continuously reflect optical photons, absorb UV photons and luminesce, emitting excess energy into the environment. We believe that not only ordinary light pressure, but also the absorption of short-wave UV or X-ray radiation by a small particle, followed by the emission of luminescent photons, will lead to dynamic consequences. Momentum of the emitted luminescent photon will cause the recoil of this small particle in the direction opposite to the direction of emission of the luminescent photon.

The time–constant process of absorption of the UV photons by a small particle, followed by the re-emission of luminescent photons, will cause the movement of a small particle in the opposite direction - luminescent thrust. In the spatial system star–small particle, where both star and small particle are located on one and the same straight line, the luminescent recoil can lead both to the approaching the small particle to the star or to its distancing from the star. Considering the crystal state of the substance of a particle proposed by us, accompanied by the anisotropy of its optical properties, it can be expected that the diameter of a small particle will be an important factor determining the direction of movement of this small particle - to or from the star. A particle of nanometer size, consisting of hundreds of thousands of atoms (molecules) can emit a luminescent photon in the direction from the star. In other words, the radiation from the illuminating star can, as it were, 'permeate' into the particle, being first absorbed and then re-emitted in the direction from the star. A crystalline particle of micrometer or millimeter size consisting of millions of atoms (molecules) can emit a luminescent photon in the direction of the illuminating star. In other words, the radiation from the illuminating star can first be absorbed by this particle, and then re-emitted in the direction of the star. The emission of luminescent photons by a crystalline particle in the forward or inverse directions will lead to a change in the spatial coordinates of the small particle, its approach or distance from the illuminating star in a real space environment, under conditions of gravity and ordinary light pressure, the processes described above will be more complex. So, in the case of small nanometer–sized particles, the luminescent thrust can lead to their deceleration, whereas for small micrometer or millimeter-sized particles - to their acceleration, at which the action of the luminescent thrust will be added to the action of ordinary light pressure. As the crystalline particle approaches the circumstellar space of illuminating star, its behavior will begin to change. By the phenomenon of luminescent thrust will lose its physical significance, and the crystalline particle will obey to the Poynting-Robertson effect. Below we will consider a specific case when a crystalline particle is located at a considerable distance from the illuminating star and the effect of gravitational forces is minimal. In fact, this is the case when the change in the spatial position of a small particle will be determined by the radiation from the illuminating star (or stars). We will consider only the case when a small particle is in a crystalline state, characterized by the optical anisotropy of its substance.

According to Wichmann (1967), the general momentum conservation equation for the case of interaction of a photon with a material surface will have the form

$$P + mv = -P' + mv' \qquad (1)$$

Here $P = h/\lambda$ is the momentum of a photon, and mv is the momentum of a material body of finite mass m. It is evident that the right-hand side of Eq. (1) describes the elastic interaction (reflection) of a photon with the surface of a material body.

Equation (1) is also applicable to our case: a photon characterized by momentum h/λ is absorbed by the substance of a small particle (inelastic interaction), which initially possesses momentum mv, and is subsequently re-emitted within a time interval of 10^{-8} to 10^{-4} s in a direction opposite to the motion of the particle. The emitted photon carries momentum h/λ', thereby imparting an additional acceleration (recoil) to the small particle in the direction of its motion.

At the same time, $h/\lambda' < h/\lambda$ indicates optical luminescence of a small particle excited by ultraviolet photons, and mv' represents the momentum of the particle after emission of the luminescent photon.

Depending on the shape and size of the particle, as well as the optical anisotropy of its crystalline substance, luminescence centers may have different spatial orientations, being located either on the irradiated side ("hemisphere") or on the non-irradiated side of the small particle.

For example, the optical anisotropy of diamond is associated with residual mechanical stress or irregular distribution of impurities (Varshavsky 1968). These physical features can lead to luminescent recoil either in the direction of motion of the particle (when luminescence centers are located on the irradiated hemisphere) or in the opposite direction (when they are located on the non-irradiated hemisphere).Of course, there may be other locations of luminescence centers. However, if they are located on the non-radiated side of the surface, the luminescent recoil can cause slowing down the movement of such a small particle.

Let us consider a specific case of a small diamond particle (the crystalline state of the substance) characterized by a spherical shape, density $\rho = 3.5\ \mathrm{g\,cm^{-3}}$, diameter $d = 100-100000$ nm, standard luminescence centers, exciting ultraviolet radiation $\lambda = 266$ nm, and luminescence radiation $\lambda = 731$ nm. We transformed Eq. (1) to calculate v' assuming a rectilinear movement of a small diamond particle with an initial speed $v = 4 \times 10^4\ \mathrm{cm\,sec^{-1}}$, for the case of emission of luminescent photons in the direction opposite to the direction of movement of this diamond particle. Assuming that each 1 nm^2 of the surface of the irradiated 'hemisphere' of this small particle can absorb 1 UV photon and also re-emit 1 luminescent photon of the optical range, we have $n_{\mathrm{abs}} = n_{\mathrm{rad}}$ where n_{rad} is a number of photons emitted by the surface of the irradiated 'hemisphere' with an area of $S_{1/2} = 2\pi R^2$. Therefore, in fact, we can write: $(P + P')\cdot n_{\mathrm{rad}}$. The inclusion of the n_{rad} coefficient into the transformed Eq. (1) made it possible to pass from the generalized case for a single photon (absorbed/emitted) to the specific case for the flux of luminescent photons emitted by the 'hemisphere' of a diamond particle of finite mass – m, of nanometer or micrometer dimensions. When this diamond particle is distancing from the illuminating star, the number of UV photons absorbed by it will decrease over time. The condition $n_{\mathrm{abs}} = n_{\mathrm{rad}}$ that we have accepted, will be expressed for the quantum yield of luminescence as $K = n_{\mathrm{rad}}/n_{\mathrm{abs}} = 1$, and for the energy yield of luminescence as $\mu = E_{\mathrm{rad}}/E_{\mathrm{abs}} < 1$. At the same time, the difference in the energies of the absorbed and emitted photons will be spent on the excitation of atomic systems of the diamond dust substance.

The results of our calculations are presented in Table 1. In the first column – the radius of the particle (r), in the second – its mass (m), and in the third – the speed (v') (taking into account the contribution of the luminescent recoil). Here we did not take into account any additional circumstances or effects. As can be seen from the table, such a diamond particle with a radius of 50 nm and an initial speed v is characterized by the largest increment of speed due to the luminescent recoil. At the same time, a diamond particle with a radius of 5×10^4 nm and with the same initial speed v, is characterized by a virtually zero speed increment. It is obvious that for the case when the luminescence centers will be located on the unilluminated 'hemisphere' of the diamond dust particle and, consequently, luminescent photons will be emitted in the direction of the diamond particle movement with an initial speed $-v$, this will lead to a relative deceleration of the movement of this diamond dust particle.

Under the conditions considered for a diamond dust particle with a diameter of 100 nm and an initial velocity $V = 0$, the change in spatial coordinates due to luminescent thrust will be insignificant on the scale of cosmic distances. This kind of diamond dust particle, moving only due to luminescent recoil, will approximately overcome 9,000,000–10,000,000 km per 10^6 year. However, despite of insignificance of such distances, this physical phenomenon will be accompanied by appropriate consequences, including a gradual change in the size and shape of dust clouds, complexes consisting of such diamond dust grains. It should also be taken into account that the spatial orientation of the luminescence centers for each selected individual diamond dust grain can be arbitrary.

Luminescent recoil can cause the acceleration of the diamond particle in arbitrary directions, including transversal. Not all of the diamond dust particles moving due to luminescent thrust in the presence of external factors and forces can make rectilinear movements. Some of them can move along curved trajectories. This means that for real dust clouds, the movement of, for example, diamond dust particles due to the luminescent recoil will be changed not so much in the size of the cloud, but predominantly in its shape – spatial geometry. This process will be the more intense the greater the influence of the gravitational forces and ordinary light pressure from the illuminating star on the dust particles. Of course, we take into account the shape peculiarities of nanometer-sized cosmic dust particles, including non-standard deviations of their surface area to their volume S/V. Therefore, in fact, the concept of hemisphere of a small cosmic dust particle used by us has a conditional character defining the boundaries of the illuminated fraction of the surface from the unlit one. For small cosmic particles of the corresponding chemical-mineralogical composition, the phenomenon of luminescent recoil can be characterized by features determined by the luminescence time of mineral phases at low temperatures. The luminescence time of a small cosmic particle, for example, a diamond particle, can be defined (Simonia 2007a) as

$$t = t' + \tau \qquad (2)$$

Where t' is the period of exposure to a small particle of the short wavelength electromagnetic radiation absorbed by it (for example, UV radiation), and τ is the period of afterglow of the cosmic particle after the termination of absorption of short wavelength radiation (after termination of luminescence excitation).

It is known that photoluminescence of a solid substance can be divided into two types: fluorescence $\tau = 0$, when the luminescence of a substance stops immediately after the termination of its excitation, and phosphorescence $\tau > 0$, when the luminescence of a substance continues after the termination of its excitation. At low temperatures, solid substances can phosphoresce for a relatively long time, with a characteristic afterglow period τ from a few seconds to several tens of minutes. At the same time, phosphorescence will be characterized by a gradual weakening of its intensity, obeying a specific pattern of attenuation associated with the value of the temperature of the solid substance and its chemical-mineralogical composition.

In our case, a diamond dust particle will move under the influence of the luminescent recoil for several minutes and even after the excitation of this luminescence ceases. In fact, the phosphorescent diamond dust particle will still move forward but irregularly (after the termination of the short wavelength exciting radiation), experiencing a gradual slowdown correlating with the law of glow attenuation.

The termination of the action of exciting radiation on a dust particle can be conditioned by only two factors: (1) an extreme unsteady process in the illuminating star or circumstellar space; and (2) a significant distance of a small cosmic particle from the illuminating star, at which the flux of exciting electromagnetic radiation (X-ray, UV) will become extremely weak, insufficient to excite the luminescence of a cosmic dust particle.

In principle, there are circumstances of chemical nature when ions of interstellar gas adsorbed or implanted into the substance of a dust particle can change the chemical composition of a nano-dust, thereby changing the luminescent properties of its substance. However, this kind of change in luminescent properties will require significant periods of time.

Taking into account the peculiarities of the shapes of small cosmic particles, the optical anisotropy of their crystalline substance and, taking into account the expression proposed by Simonia (2007a) for the luminescence intensity of cometary dust particles, we express the luminescence intensity of a small cosmic particle (for example, a diamond dust particle) as follows:

$$I_L = \frac{S'}{2} \int_{E_1}^{E_2} F \, dF \qquad (3)$$

Where $S'/2$ is the area of the luminescent 'hemisphere' of a small cosmic particle, F is the energy of photoluminescent photons (of the corresponding wavelength) emitted by 1 nm^2 of the luminescent surface of the particle under the condition $E_2 > F > E_1$. Obviously, for the case $S' = 4\pi r^2$, when the luminescence centers are homogeneously distributed over the surface of a small cosmic particle, its luminescence intensity I_L will be maximal, but such a small particle will be stationary without making any movements, including forward movement.

As an exciting radiation of a small particle luminescence, we assumed UV radiation in the range of 200–390 nm. At the same time, the phenomena discussed above can be characterized by similar properties under other conditions as well, when the wavelength of the exciting radiation will be $100 < \lambda < 200$ nm, and the wavelength of the luminescent radiation of a small particle will be $390 > \lambda' > 200$ nm, i.e., the case of ultraviolet luminescence of a small cosmic particle. There may be other manifestations too, for example, X-ray luminescence of the small cosmic particles, including metal particles. It is clear that in real conditions, a small cosmic particle will be influenced by a number of external factors and forces, including gravity, light pressure, and collision phenomena (dust–dust, gas–dust), etc. The primary characteristics of a moving small cosmic particle will also be important, including its mass, size, initial velocity, and temperature of its substance.

Taking a small cosmic particle in the first approximation as a spherical dust particle of a nanometer size, of a certain chemical-mineralogical composition, the substance of which would be characterized by a crystalline state and assuming the absence of external factors and forces, we showed that such a dust particle could move, accelerate or slow down under the action of luminescent photons (causing luminescent recoil) emitted in the appropriate direction. One of the determining factors of this kind of movement caused by the luminescent thrust is the optical anisotropy of the dust particle substance, in which the luminescence centers should be spread out only on a fragment ('hemisphere', a limited volume) of the dust particle substance. The forced emission of an amorphous dust particle would be characterized by an isotropic distribution of luminescence centers over the surface of the dust particle and naturally would not lead to the appearance of a preferred direction (the only direction) of the luminescent recoil. Such a particle under the action of luminescent photons would remain stationary; its spatial position would not change for a certain period of time. It should also be added here that solid crystalline substances are characterized by a high luminescence yield, whereas substances in the amorphous state luminesce weakly or do not luminesce at all.

So, the minimum conditions for the occurrence of luminescent thrust in a small cosmic particle are: (1) nanometer or micrometer sizes of a particle; (2) a preferred location (one of the 'hemispheres') of luminescence centers in the substance of a particle; crystalline state of this substance; (3) a significant luminescence yield of the particle substance $E_{\rm rad}/E_{\rm abs} \geqslant 50\%$; (4) presence of noticeable absorption bands in the X-ray or UV ranges of a particle substance spectrum; (5) absence of impurities (ions) quenching luminescence in the particle substance; (6) reemission by a substance of a particle of the absorbed energy in the form of UV or optical photons (absence of non-radiative transitions).

As a matter of fact, these are the minimum and sufficient conditions for the occurrence of a luminescent recoil force applied to a small cosmic particle as a result of absorption by a small particle of the short wavelength electromagnetic radiation and return of excess energy by such particle in the form of luminescent photons emitted in any one preferred direction.

These conditions narrow the list of cosmic dust particles that can be characterized by the phenomenon of luminescent thrust. Not all representatives of the cosmic dust particles can have the appropriate size, chemical and mineralogical composition, and crystalline state of substance, low albedo, and high absorption coefficient in the short wavelength range of the spectrum and high luminescence yield. However, a number of substances can satisfy the proposed conditions, namely, carbon in the crystalline state and some silicates. This means that nano- and micro-dispersed diamond, forsterite, enstatite and other cosmic dust can be characterized by luminescent thrust during the luminescence of their substances.

Predetermining condition for the occurrence of luminescent recoil, during the luminescence of a small cosmic particle is the emission of luminescent photons by a particle in only one concrete direction. For the occurrence of such a natural selectivity, it is necessary that the substance of the cosmic dust particle be in a crystalline state, which in turn would determine the optical anisotropy of this substance. Ideally, in the laboratory conditions (vacuum, temperature $T < 77$ K) under the influence of the exciting ultraviolet monochromatic radiation, for example with a wavelength of 220 nm and, provided that a small particle with radius r will have a spectral 'window' of absorption in the range of 219–221 nm and a reflection coefficient less than 0.001 in the UV and optical ranges ($\lambda' > 221$ nm), we can expect a rectilinear and conditionally uniform movement of this small particle with a speed v under the influence of luminescent photons. Ultraviolet radiation ($\lambda = 220$ nm) of the laser can cause the movement of a small particle due to the luminescent recoil for a certain period of time. This movement can be conditionally uniform if the luminescent photons are emitted in the direction opposite to the direction of movement of the particle. When a small particle is moving away from the UV radiation source, while absorbing fewer and fewer UV photons, the particle will experience a gradual slowdown. The ideal laboratory conditions considered by us, including exposure of a small particle to monochromatic UV radiation and an extremely small reflection coefficient of the substance of such a particle, determine the specific nature of its movement.

In the space environment (but away from powerful gravitational fields), there are two factors that can determine the movement of a small dust particle: light pressure and luminescent recoil. The first factor, the light pressure, is realized when the incoming radiation is reflected. The second factor, the luminescent recoil, is realized when excess energy is re-emitted into the environment in the form of luminescent photons. A dusty particle can simultaneously reflect incoming radiation and re-emit part of the absorbed energy in the optical range, i.e., to luminesce.

In other words, two processes can take place in the space environment: reflection and luminescence. Based on the above, we can conclude that these two processes are concomitant and complementary. If the emission of luminescent photons occurs only in one direction, then these two concomitant processes (reflection and luminescence) will cause the movement of a small particle in the radiation field. Both of these physical processes manifest themselves in the interaction of radiation with a substance in the form of the receipt or recoil of energy and momentum by a small particle. This is a kind of unifying principle of the processes of reflection and luminescence.

At the same time, there are fundamental differences due to the actual difference in the nature of these phenomena. According to Wiedemann (1888), luminescence is the emission of photons, which is excessive over thermal radiation, and continues after excitation ceases for a time many orders of magnitude greater than the period of light oscillations.

This definition of Wiedemann (1888) separates luminescence from scattering, the reflection of light, which stops almost instantly, during 10^{-15} seconds after the termination of external irradiation of the object with light. With the luminescence of the type of fluorescence, the duration of the excited state of atoms and molecules of the substance is 10^{-8} seconds, and the luminescence of the phosphorescence type is 10^{-4} seconds. Scattering, reflection of light by substances is a 'fast' phenomenon, whereas luminescence of the same substance is a 'slow' phenomenon.

For our case, this means that the light pressure on a small cosmic particle will almost instantly cause its movement, whereas the luminescent thrust occurs with some delay. The movement of the cosmic nano-particle may be preconditioned due to the 'fast' light pressure and the time-lagging luminescent recoil. These various physical phenomena will be characterized by their own time scales.

In the space environment and in other real conditions of motion of a small particle under the influence of light pressure and luminescent recoil, these are two complementary, concomitant physical phenomena within the same physical system but at different time intervals. However, in our opinion, there may be an ideal case when a small particle will be irradiated with monochromatic radiation, have a narrow spectral 'window' of absorption and re-emit luminescent photons of the same wavelength – resonant fluorescence. In this case, all the absorbed energy will be re-emitted in the form of luminescent photons into the environment in a certain direction. In the case of resonant fluorescence, all the energy absorbed by the small particle will be re-emitted and the movement of this small particle will be caused only by the luminescent recoil in the actual absence of light pressure. This case is, of course, ideal, but in principle possible. We have shown that in the interstellar medium, far from powerful gravitational fields, hard electromagnetic radiation from stars absorbed by crystalline dust particles can be re-emitted by these particles into the environment in the form of optical (luminescent) photons, which cause a change in the speed of dust particles and, in some cases, in the direction of their movement.

These are the dynamic consequences of luminescence of interstellar crystalline dust particles. Luminescent crystalline dust particles of the interstellar medium will change their spatial position over long periods of time.

4 DISCUSSION

Luminescent photons emitted by a crystalline cosmic particle in any selected direction will cause a luminescent recoil, which in turn, in terms of the constant process of luminescence of this particle, will lead to its movement in the direction from the source of excitation (star), or towards it. At the same time, luminescent thrust in most cases can be a concomitant process to the process of light pressure on a small particle, contributing to the acceleration (movement) of such a small particle.

Our reasoning concerned only the dust particles being in a crystalline state. There is no doubt that the light pressure and the luminescent recoil are two different phenomena, occurring at different rapidities (10^{-15} sec for reflection/scattering and 10^{-8}–10^{-4} sec for luminescence). In the case of luminescence of the phosphorescence type, the process of relaxation of the atomic–molecular systems of a substance of a dust particle will occur for a conditionally long time from the triplet state.

We showed also that for the case of the resonant fluorescence of a small particle, all the absorbed energy will be re-emitted into the environment at the same wavelength, which will cause the movement of a small particle only under the action of luminescent photons. In principle, this can be considered as the actual absence of light pressure, or as a kind of transformation of the 'fast' reflection process into the 'slow' luminescence process of the particle. In this case, the resonant fluorescence is not enough; therefore, an extremely low albedo of the particle and the presence of characteristic absorption bands in the spectrum of the substance of this particle will also be necessary.

These circumstances lead us to the conclusion that the motion of a cosmic dust particle under the action of resonantly emitted luminescent photons is an ideal case that can take place only in very specific conditions, for example, in conditions of extremely low temperatures. It would be interesting to conduct laboratory experiments on the acceleration of nanometer particles by resonant luminescent photons in the beam of an ultraviolet laser.

We found it necessary to verify our results (Table 1) for the case of a small diamond dust particle with an absorption band in the shorter wavelength range of the UV spectrum and, respectively, with luminescent emissions in the shorter wavelength range of the optical spectrum. According to Tarashchan (1978), the maximum of the excitation spectrum of the blue luminescence of diamond (427.5 nm) has a wavelength of 230 nm. Based on our transformed Eq. (1) for the case of a diamond dust particle with a diameter $d = 1000$ nm and an initial speed $v = 4 \times 10^4$ cm sec^{-1}, we calculated the value of $v' = 40000.0161$ cm sec^{-1}.

The obtained value represents the luminescent contribution to the acceleration of a diamond dust particle. This result fully confirms the validity of our conclusions. In the astrophysical projection of the problem, an interesting aspect is revealed. It is known that near the wavelength $\lambda \approx 217.5$ nm there is a fundamental interstellar absorption observed in different directions in the spectra of various galactic objects. The origin of this absorption is still debated. A number of studies have considered the possible role of fine-dispersed graphite dust, which can effectively absorb ultraviolet radiation of the mentioned wavelength (Ehrenfreund et al. 2006; Herrero et al. 2022).

We assume that if a crystalline carbon–diamond nano-dust can absorb UV radiation near 220 nm, then it will re-emit luminescent photons in the range $\Delta\lambda = 330$–430 nm. This means that interstellar dust clouds consisting of nanometer-sized diamond dust particles can contribute to the formation of this fundamental absorption, with slow but constant motion under the action of luminescent photons emitted in the near ultraviolet or in the short-wavelength region of the optical spectrum. The blue glow of circumstellar dust may be a manifestation of this kind of phenomenon. If, however, these dust clouds and complexes of nanometer-sized diamond dust re-emit an excess of energy in the range $\lambda < 300$ nm, their presence may be generally undetectable by ground-based instruments at all.

We believe that the fundamental absorption band near 217.5 nm can be caused by the absorption of nanometer diamond dust moving under the action of luminescent photons, slowly changing the symmetry forms of cloud formations.

Small cosmic particles in the form of micrometer and nanometer dust particles of various chemical and mineralogical composition can also luminesce under the action of charged particle fluxes (the phenomenon of cathodoluminescence).

Bombardment of nano-dust particles by fast electron fluxes can lead to cathodoluminescence of these nano-dust particles with the subsequent occurrence of the phenomenon of luminescent recoil. However, the cathodoluminescence of mineral substances is characterized by a flash nature and a lower quantum yield; therefore, in fact, the movement of cosmic dust particles under the action of cathodoluminescent photons can be slower and irregular.

It is necessary to keep in mind other possible phenomena, namely X-ray luminescence, infrared fluorescence and thermoluminescence of fine-dispersed cosmic dust (Simonia 2004, 2007a, 2016, 2007; Simonia & Gucsik 2019). The phenomena considered will also depend on the shape of a small particle and, in the case of nano-dust, on the non-standard ratio of its surface area to volume. The depth of penetration of electrons into the substance of the nano-dust particle will be different, varying depending on the energy of the electrons, the physicochemical characteristics of the substance of the dust particle and other factors. If a small cosmic particle is characterized by the presence of unstable isotopes, this may contribute to the direction of the luminescent recoil. This may be especially true for particles of micrometer sizes.

The main differences of the phenomenon of luminescent thrust of cosmic crystalline dust particles from the Poynting–Robertson effect are: (a) the phenomenon of luminescent thrust can cause the movement of a dust particle only far from powerful gravitational fields; (b) the phenomenon of luminescent thrust can only cause rectilinear movement of a dust particle; (c) the phenomenon of luminescent thrust of a cosmic dust particle can lead to an increase in the distance between the radiation source (star) and the dust particle (in most cases). In other words, if a cosmic dust particle is subject to the Poynting–Robertson effect, it slows down and gradually falls onto the star in a spiral trajectory, while a dust particle subject to the luminescent thrust phenomenon accelerates, gradually moving away from the star in a rectilinear trajectory.

Luminescent recoil of cosmic dust is a localized physical phenomenon, relevant only for a specific class of dust particles far from powerful gravitational fields. In contrast, ordinary radiation pressure and the movement of cosmic dust due to the Poynting–Robertson effect are global phenomena.

We have considered here the phenomenon of luminescent recoil for small cosmic particles of micrometer and nanometer sizes for the case of a crystalline state of substance of small particles. We focused our attention mainly on the individual process of emission of luminescent photons by a crystalline substance of a small particle. We have shown that, under the action of short-wavelength electromagnetic radiation, a small cosmic dust particle can emit a flux of luminescent photons, which conditions the luminescent thrust of a small dust particle. It should be emphasized that we considered the case when a small cosmic dust particle is located far from powerful gravitational fields and emits luminescent radiation only by a fragment, area or 'hemisphere' of its surface.

Table 1. Luminescent recoil for the cosmic dust particle.

Radius r (nm)	Mass m (g)	V' (cm sec^{-1})
50	1.785×10^{-15}	40000.00298
500	1.785×10^{-12}	40000.0003
5000	1.785×10^{-9}	40000.00003
50000	1.785×10^{-6}	40000.

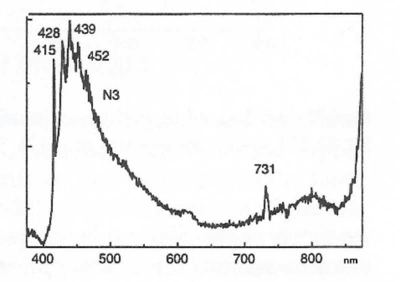

Figure 1. Photoluminescence spectrum of diamond (N3 centers) (Gaft et al. 2005).

5 CONCLUSION

Interplanetary and interstellar dust is exposed to external factors and forces. In particular, micrometer and nanometer dust particles of various chemical and mineralogical composition, sizes and shapes are constantly exposed to hard electromagnetic radiation and fluxes of fast charged particles. Individual dust particles and cloud dust formations evolve by changing their composition, shape and position. We have shown that in addition to light pressure, the movement of small dust particles can also be caused by the phenomenon of luminescent recoil. At the same time, the radiations that cause this phenomenon can be both hard electromagnetic radiation and fluxes of fast electrons and protons. We have also shown that the luminescent thrust of a small particle will cause a change in its spatial position over a long period of time. The luminescent recoil will have its contribution in the process of acceleration of cosmic dust.

It seems advisable to conduct laboratory experiments at low temperatures for nanometer and micrometer crystalline mineral grains with a small albedo, when the luminescence of these grains is excited by monochromatic ultraviolet radiation. Such experiments can expand and concretize the understanding of the peculiarities of the phenomenon described by us.

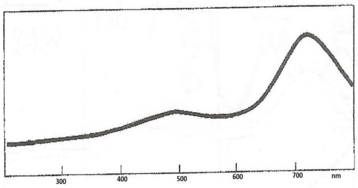

Figure 2. Cathodoluminescence spectrum of forsterite from the Murchison meteorite (Gorobetz & Rogozhin 2000)

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