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POSSIBLE THERMOLUMINESCENCE OF THE SOLID COMETARY SUBSTANCE: THERMOLUMINESCENCE OF COMETARY SUBSTANCE

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ABSTRACT

The article describes a mechanism of the possible thermoluminescence of solid cometary substances, including dusty halos. We propose to consider comet flares as the thermoluminescence of the cometary ices and mineral dust. The article provides the results of some laboratory experiments on frozen phosphorescence of a number of minerals (quartz, forsterite, and diamond) conducted over the past several years and relevant for reviewing the given problem. We also propose a concept of the comet's luminescent relictography and some scientific initiations. Properties of red and blue thermoluminescence flares of cometary halos are described, and we consider the similarity of thermoluminescence and cathodoluminescence processes of cometary dust. Various aspects of the problem are under discussion.

Key words: comets: general – comets: individual (C/1995O1 Hale–Bopp) – dense matter – radiation mechanisms: thermal

1. INTRODUCTION

The study of comets and other small bodies of the solar system is an important direction in modern astrophysics. Bodies within the solar system are exposed to solar X-ray and ultraviolet radiation, as well as to fluxes of solar wind charged particles. These photons and charged particles may cause luminescence from the surfaces of atmosphereless bodies, including comets and planetary satellites, especially if one considers that such bodies do not present any permanent magnetic fields to protect them from impact with solar wind particles. Solar UV photons and charged particles may cause also photo- and cathodoluminescence of cometary minerals and icy halos. These luminescence phenomena were discussed for the first time by Sinonia & Simonia (2004) and Simonia (2007, 2011). Detection and characterization of these phenomena from small bodies in the solar system could become an efficient new method for the study of their surface and atmosphere composition, particularly for studying mineralogy and the possible presence of silicate and carbonaceous dust. The present work is dedicated to the consideration of possible thermoluminescence phenomena of cometary dust and ice.

2. THERMOLUMINESCENCE OF COMETARY DUST AND ICE

It is known that cometary dust is subject electromagnetic radiation and fast particle fluxes. The Sun is the source of the shortwave electromagnetic radiation and particles of different energies that interact with cometary dust in the interplanetary medium. The interaction of radiation with cometary dust causes a number of well-known phenomena, including absorption, scattering, and luminescence. The problems of absorption and scattering of radiation by cometary dust are also rather well studied.

Dust particles of different sizes, when absorbing passing energy, transform it, in many cases, into heat- or optical-range radiation—i.e., luminescence. One or another peculiarity of the result of dust–radiation interactions, including the formation of a refractory mantle, the enrichment of dust particles with impurity ions, the change of the aggregation state, and the peculiarities of optical luminescence and IR fluorescence spectra, will depend on the energy of radiation, the size and chemical composition of dust particles, and other factors. However, it is assumed that there is an interaction between dust particles with UV radiation and electrons of relatively small energies. In our opinion, there is also another case: namely, the interaction of cool cometary dust with gamma rays, hard X-rays, and different high-energy particles, including relativistic particles. We hypothesize that the atoms of cool dust matter absorbing the energetic particle, will make the transition to a metastable state and can remain there for a rather long time under conditions of low temperatures and the absence of collision with other dust particles. Thus, cool cometary dust can serve as a "reservoir" of absorbed energy, and in any particular case, each dust particle (microreservoir) will retain a strictly determined amount of absorbed energy. Of course, the process of energy accumulation will be justified for sub-surface substances of cometary nuclei, including dusty zones and patches.

Pringsheim (1951) noted that, for atomic systems under rather low-temperature conditions, the transition of atoms from metastable state M to excited state F is not practically observed. At the same time, when the light is absorbed, the transitions from ground state N to F, as well as from F to M, are made without difficulty. This means that the phosphorescence of the corresponding matter is excited and "frozen." If we then increase the temperature of this matter, the absorbed energy is released and begins to radiate as a bright flare without a new excitation. Thermoluminescence is the indication of "frozen" phosphorescence in certain temperature intervals. Koike et al. (2002a, 2002b) irradiated the minerals of forsterite, orthoenstatite, olivine, crystalline silicone, etc., by gamma-ray and fast neutron fluxes under liquid nitrogen temperatures. The subsequent quick heating of the irradiated minerals up to room temperature led to their thermoluminescence in long-wavelength regions of the optical spectrum. Under the condition of low temperatures, samples of the previously mentioned minerals, at millimeter-level dimensions, accumulated the energy of absorbed gamma photons and fast neutrons. It is obvious that further heating of such samples returned the atoms from their metastable state to an excited state, with further reradiation of the energy in the optical spectrum. Koike et al. (2002a, 2002b) studied the case of frozen phosphorescence of minerals, trying to explain the nature of reflection nebulae extended red emission. Photoluminescence of reflection nebula dust was studied by Duley et al. (1997) and Witt & Vijh (2004). In our opinion, the phenomenon of the frozen phosphorescence of dust has much wider and more universal significance in the process of universal matter evolution, including cometary matter, than has previously been realized. The process of "freezing" (accumulation) the energy absorbed by fine-disperse dust particles probably takes place permanently in the cosmic medium. We assume that rather similar processes might be pertinent to the case of cometary dust. We assume that the fine-dispersed particles of the mineral and icy halo of comets (as well as the mineral and icy components of the cometary matter, in general) can demonstrate a bright themoluminescence in certain conditions. The sub-surface substance of cometary nuclei (including dust particles) may accumulate energy from the solar electromagnetic and corpuscular radiation. The Sun irradiates permanently the substance of cometary nuclei. High-energy photons, fast electrons, and protons may penetrate the sub-surface layer of nucleic substances at certain heliocentric distances. This irradiation takes place at any chosen moment of time. The energy of absorbed photons (particles) is accumulated by the matter of dust particles, making their transition to the metastable state a result of the absorption process. Each microscopic dust particle, with the atoms of its matter in a metastable state, is a sort of microreservoir of absorbed energy. Under the conditions of stable low temperatures $T < 80$ K, the energy accumulated by dust particles can be retained for a long time; only as a result of quick heating of the dust will the absorbed and "frozen" energy be released as optical radiation—i.e., thermoluminescence. It is natural that well-heated dust will not be able to accumulate the absorbed energy, whereas the dust located at a significant distance from the Sun will accumulate and retain the absorbed energy without difficulty under the conditions of stable low temperatures. This means that energy accumulation by sub-surface substances of cometary nuclei could occur at far- or mid-heliocentric distances, but release of energy (thermoluminescent flare) occurs at shorter distances. At relatively short heliocentric distances, comet mineral halos may demonstrate that thermoluminescent flares are macrophenomena of dust-particle complexes. In other words, fast heating of newly delivered cool dust particles in cometary halos may cause a release of the frozen energy as intense thermoluminescent flares of the halos' substance. Such a phenomenon could be registered by observers as an active process in that specific comet in the form of flares or flashes. Regular cometary flares of an unknown nature might be explained by this proposed mechanism. Taking into account the movement of cometary nuclei and dust, the possibility of its heating by the solar UV radiation, the frequent collision processes of dust–dust or dust–gas type, and other dynamical processes, one can conclude that with the process of absorption and accumulation of energy by dust, the process of accumulated energy release by dust particles may simultaneously take place at certain heliocentric distances.

Thus, in cometary substances, two opposite processes may take place permanently: the accumulation of energy by dust and the release of energy by dust. If these processes are balanced, it can be expressed as

$$nE_{\text{abs.}} = n_1(E_{\text{rad}} + E_{\text{int}}) \tag{1}$$

where $n = n_1$ is the number of dust particles in some separate closed volume or in the halo as a whole. Here, E_{abs} is the absorbed energy, E_{rad} is the energy radiated in the form of thermoluminescence, and E_{int} is the energy consumed for internal processes.

At the same time, in the cometary nuclei at any chosen moment of time t, there will be a finite number of dust particles n_2, neither accumulating nor releasing the energy. This dust has already absorbed a certain amount of energy and retains it until a certain moment of time t_1—the moment of larger external effects (heating, collision, outburst, and etc.). Sub-surface dust of such kind, which holds the absorbed energy, can be named dark dust.

Cometary dust can be divided into two classes: (a) energy accumulating and (b) not energy accumulating. Such a division of dust is caused by a number of factors, including the chemical–mineralogical composition of dust particles (some organic compounds have very deep metastable levels), dust temperature, size of dust particles, density of dust complex, etc. However, the temperature factor is more important. In the solar system, a certain boundary or temperature limit probably exists, below which matter, including cometary dust, becomes able to accumulate absorbed energy. Such limit, most likely, is near $T \approx 80$ K. We propose calling this limit the horizon of accumulation.

The dust having temperature $T < 80$ K, i.e., that dust existing below the horizon of accumulation, can accumulate absorbed energy. The dust having temperature $T > 80$ K, i.e., the dust existing above the horizon of accumulation, cannot accumulate absorbed energy. Obviously, the micron-scale or larger dust particles can accumulate the absorbed energy. Dark dust is below the horizon of accumulation. One cannot exclude the possibility that interplanetary gas in the form of the complex of collisionless polyatomic molecules (e.g., PAHs), having the temperature $T < 80$ K, i.e., existing below the horizon of accumulation, will also retain absorbed energy for a long period of time. The significant factors are that (1) the cometary nuclei dust (possibly including the frozen gas) can hold the absorbed energy for a rather long period of time; and (2) the energy accumulated by nucleic dust is still impossible to register. Consequently, dark dust can hide a certain amount of the energy of the cometary substance. In fact, it may be impossible to detect this hidden energy until the moment of its release.

If, in the inner layers of the cometary nucleus, there is micron-scale dust under conditions of super-low temperatures ($T < 30$ K), it can probably retain the accumulated energy for extremely long periods of time. Such dust could carry a significant part of the non-registered cometary substance energy.

Cometary dust particles below the horizon of accumulation and holding the energy of at least one gamma-photon are an important element in the process of evolution of solar system matter, requiring special attention not only from the perspective of astrophysics, but also from the viewpoint of cosmogony. Cometary dust accumulates the energy of absorbed fast

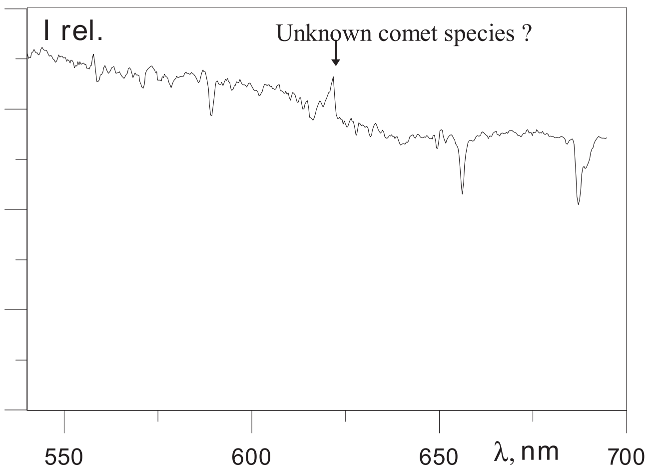

Figure 1. Red range of the spectrum of the comet Hale–Bopp (the nucleus region). 1997 July 10 (Churyumov et al. 1997).

neutrons and other particles, as well as the gamma rays from the Sun. Dust below the horizon of accumulation may also interact with diffuse galactic gamma-rays, accumulating the absorbed energy and keeping it until the moment of quick heating.

We propose expressing the total energy accumulated by cometary dust as

$$E = KNF \tag{2}$$

where K is the coefficient expressing the probability of the process of accumulation of the energy absorbed by dust, $K = f(T, D)$, where T and D are the temperature and diameter of a dust particle, respectively. In general, $0.9 > K > 0.1$. When $K = 0.1$, that means only 10% of that dust is at temperature $T < 80$ K, i.e., below the horizon of accumulation. Here, N is the total number of dust particles in the corresponding comet and F is the power of radiation absorbed by dust particles.

Rather wide emissions of an unknown nature have been detected in the spectra of several comets. Such emissions fall outside the range of standard unidentified cometary emissions as well. They might be good candidates to express thermoluminescent emissions in accordance with the proposed mechanism. In the spectrum of Hale–Bopp (C/1995O1), an unknown comet emission was detected near 6200 A (Figure 1; Churyumov et al. 1997). This feature is a good candidate to demonstrate thermoluminescent emission of cometary substances. Figure 2 shows the spectra of forsterite themoluminescence obtained by and described in Koike et al. (2002a). The forsterite micrograins obtained through grinding and irradiated by gamma rays have demonstrated a bright thermoluminescence when heated up to $T \approx 160$ K. At the same time, intense thermoluminescent emission's peak is observed near 6500 Å.

As seen, an unknown emission in the spectrum of the Hale–Bopp (C/1995 O1) comet (Figure 1) and the thermoluminescent emission of the forsterite micrograins correlate in the spectral positions and profiles. When attempting to achieve (and expecting) full and unambiguous identification of both the observed emissions and those elicited under laboratory conditions, we should not forget about the serious differences between the physical conditions of the cometary and laboratory substances, including the variations in temperature of the substances, power of accumulated radiation, masses of individual micrograins, natural impurities in the form of corresponding ions, etc. However, regardless of all such differences, the physics of the phenomenon for cometary conditions will be one and the same, assuming (1) accumulation (absorption) of gamma and other types of radiation by the mineral and icy components of the cometary substances; (2) preservation of the accumulated energy by the cometary substance (in low-temperature conditions) over a long period of time; and (3) release of the energy accumulated by the cometary substance, in the form of a bright flare, as a result of heating the cometary substance.

Ices and mineral complexes of the cometary nuclei and the atmospheres are able to accumulate the absorbed energy, hold it for a long time, and release this energy as an optical flare via heating of the cometary substance.

3. THERMOLUMINESCENCE OF COSMIC SUBSTANCES —ASTROPHYSICAL PROJECTION OF THE LABORATORY ANALYSIS

Studies of the thermoluminescence minerals of meteorites have been conducted over a long period of time and essential data have been obtained regarding the characteristic features of meteorite silicate mineral thermoluminescence (Durrani & Christodoulides 1969; Sears et al. 1999; Benoit & Sears 2001). A direct application of these data in comparative analysis for the purposes of identifying the unknown spectral features of comets and other small solar system bodies is not always possible, owing to significant differences between laboratory and space conditions. In the works of Koike et al. (2002a, 2002b, 2006) the thermoluminescences of a number of minerals are studied, including forsterite, quartz, enstatite, magnesite, calcite, etc. These laboratory investigations have shown that (1) the thermoluminescent bands of forsterite and other minerals become narrow with increasing the intensity of these emissions; (2) each subsequent reirradiation of forsterite mineral by gamma rays led to the strengthening of its thermoluminescence and a larger structuring of the spectrum of this thermoluminescence; and (3) in some cases, the minerals, including forsterite, can demonstrate rather similar spectra in their thermoluminescence and photoluminescence.

Based on these results, we may conclude generally that the fine-dispersed cometary silicate dust within a 150–170 K temperature range can demonstrate a bright thermoluminescence characterized by relatively narrow emission bands in the 6000–7500 Å range. Moreover, fluxes of the solar and galactic cosmic rays, as well as repeating gamma-flares, can intensify the thermoluminescent emissions of solid cometary matter—making their spectra more complex structurally. After weakening the short-lived thermoluminescence flares of the silicate cometary halo, the solar UV radiation can stimulate the appearance of the emissions; however, in this case, they will have a photoluminescent nature.

In the works by Koike et al. (2002a, 2002b, 2006), it is shown experimentally that the thermoluminescence intensity of the minerals forsterite, enstatite, calcite, etc., is rather high, and increases along with increasing the temperature of their substances. It is also shown that irradiation of these minerals with gamma rays leads to a change in their color from white to violet. As the experiments show, the thermoluminescence spectra of forsterite and alumina (α-Al_2O_3) irradiated with gamma rays and neutron fluxes are characterized by the

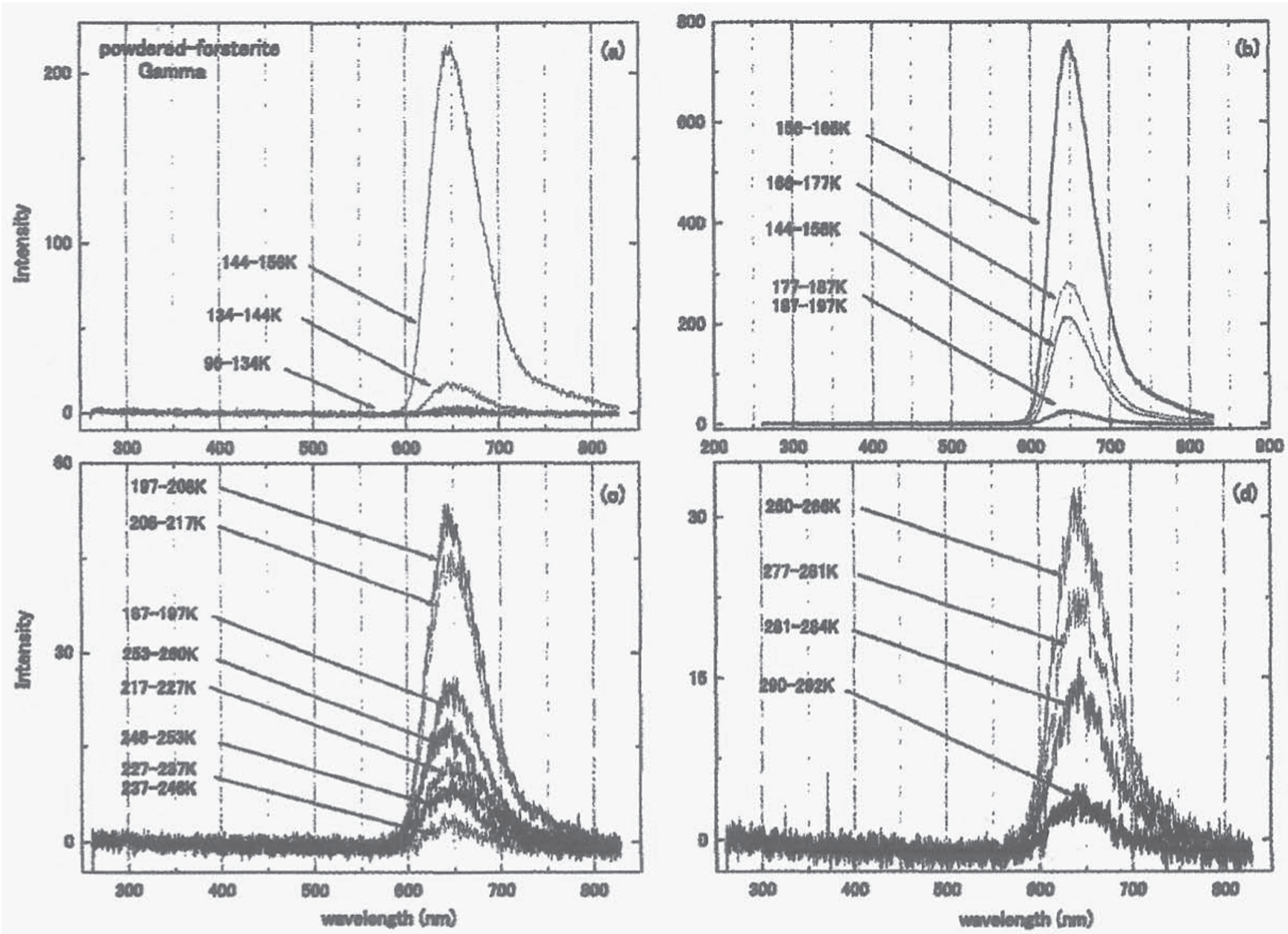

Figure 2. Thermoluminescent spectra of powdered forsterite. The warming temperature increases from panels (a) to (d). The intensity becomes stronger at 144–177 K and strongest at 156–166 K, but the intensity suddenly grew weak at higher temperature (Koike et al. 2002a).

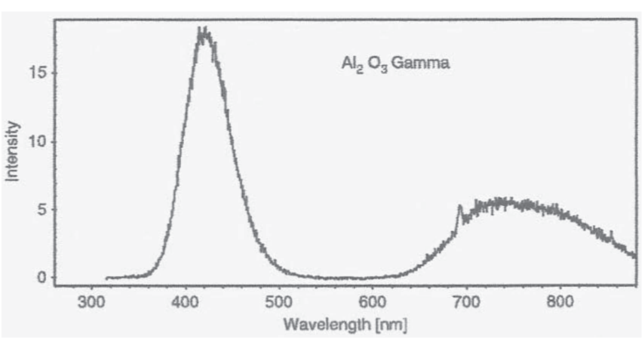

Figure 3. Thermoluminescent spectrum of α-Al_2O_3 at 235–242 K after gamma-ray irradiation. The strongest peak appears at about 420 nm, in addition to another at 730 nm (Koike et al. 2006).

existence of two wide bands of emission near 4200 and 7300 Å. Figure 3 represents the thermoluminescent spectrum of α-Al_2O_3 (Koike et al. 2006). Table 1 provides data regarding the thermoluminescence emission band wavelengths for the minerals irradiated in advance with neutron fluxes and gamma rays (Koike et al. 2006).

As to the case of the mineral cometary halo, this can mean that as a comet approaches the Sun, an intensity of thermoluminescence of the fine-dispersed mineral particles of

Table 1
Peaks of Thermoluminescence Wavelength after Neutron Irradiation (Blue) and after Gamma-Ray Irradiation (Red; Koike et al. 2006)

Sample	Peak of Blue TL (nm)	Peak of Red TL (nm)
Calcite	420–520	620–630
Magnesite	510–530	640–680
Fused quartz	420–520	600–650
Alumina	410–430	700–820
Forsterite	340–500	630–670

the halo will increase. At the same time, solar gamma rays may cause a change of color (from bright to dark) of the halo of mineral particles, which may entail a decrease of their albedo; this, in turn, may increase the ratio of emission intensity of the thermoluminescence and the elastic scattering of solar optical photons by the mineral particles of the halo.

The astrophysical projection of the above-mentioned results of the laboratory experiments may also be expressed in the detection of the color-regularized thermoluminescent flares of the comets; namely, the blue and red thermoluminescent flares. At the same time, the mutual complementary or interleaved fluxes of the neutrons and gamma rays may precondition (prepare) the occurrence of the blue and red thermoluminescent flares, correspondingly. The exact timing of flares depends on the heliocentric distance of the comet; the temperature of the nuclear substance and the released dust; the specific chemical–mineralogical composition of the dust substance (depth of metastable levels), and other factors, in other words, the time of any given flare may depend on multiple variables. However, the accumulation and release of the absorbed energy in the conditions of the increasing temperature of the substance (e.g., approach of a comet to the perihelion) may have either a synchronic or an asynchronic nature with a certain value of delay. In addition, the thermoluminescence spectra of a number of minerals, including forsterite, obtained by Koike et al. (2002a, 2002b, 2006) with the first approach, are similar to the spectra of the cathodoluminescence of the same minerals (Gucsik et al. 2013). The cathodoluminescence of the forsterite micrograins caused by fast-electron fluxes may also occur spectrally in the form of two bands of emission in the blue and red areas of the optical spectrum. Nano- and micrograins of the mineral halo of comets can also release absorbed radiation via the mechanism of cathodoluminescence while interacting with solar wind particles. Based on the preceding evidence, we may assume that the bright luminescent flares of a comet's mineral halo may sometimes have a dual nature, based on the mechanism of energy accumulation (thermoluminescence) and rapid processing of the absorbed energy (cathodoluminescence). The color-regularized feature of the luminescent flares of the cometary halo can make them easily distinguished from the solar optical radiation scattered by the dust. The appearance of the blue excess in the comets' spectra was revealed by Bobrovnikoff (1927a, 1927b).

Sinonia & Simonia (2004) and Simonia (2007, 2011) have shown that, for the cases of icy and silicate cometary halos, consisting of frozen organic and mineral grains, the ratio of the photoluminescent flux of the grains $F_{\rm Lum}$ to the flux of the solar radiation scattered by the grains $F_{\rm scat}$ at one and the same wavelength is $F_{\rm Lum}/F_{\rm scat} > 1$, for the most part.

This factor alone predetermines the occurrence of easily detectable photoluminescent emissions in the form of narrow lines in the optical spectra of comets.

It should be taken into account that the photoluminescence of the solid substances, in general, is a stable and a prolonged phenomenon, whereas the thermoluminescence of the same substances has a flaring nature and is characterized by a higher intensity.

One of the important features of the thermoluminescence of solid substances is a "glow curve," which shows a functional dependence of thermoluminescent intensity on the temperature of a substance $I = f(T)$. The metastable levels of the atomic systems (or the traps in crystals) determine the position of relevant peaks in the glow curve. Each metastable level corresponds to a peak of the curve. Therefore, the glow curve of the thermoluminescence may consist of a series of peaks.

The glow curve of thermoluminescence depends also on the power of exciting radiation (e.g., the gamma ray). In cases of numerous substances, increases in the power of exciting radiation lead to the growth of the thermoluminescent intensity.

Karczmarska et al. (2012) investigated thermoluminescence of the Chemical Vapour Deposition (CVD) diamond stimulated by gamma rays at different doses within a 0.6–55 Gy range. The thermoluminescent signal becomes detectable starting at the 9 Gy level (Figure 4). As seen in the figure, the maxima of the thermoluminescent intensity of the CVD diamonds is always located at 230°C. Thermoluminescent intensity in the maximum increases along with increasing doses of gamma radiation. Thus, for the given case, the thermoluminescent intensity in the maxima depends functionally on the dose of the exciting radiation. The astrophysical supplement of these laboratory results is obvious. If we assume the existence of diamond dust particles of micron and submicron sizes in the mineral cometary halo (or in the fluxes of the dust released from the nuclei) and convert the temperature scale (Figure 4) into the scale of the comet's heliocentric distance, it becomes clear that the maximum of the thermoluminescence of the comet's diamond dust may coincide with the perihelion, whereas its minimum is near the aphelion region of the orbit. Energy long retained by the diamond dust is released in the form of a bright red thermoluminescent flare under conditions of increased temperature of the substance and dose of exciting radiation. Near the aphelion of the cometary orbits, in conditions of lower temperature and reduced solar radiation, the diamond dusts' thermoluminescence will be a rare phenomenon. At greater distances, especially for the case of the long-periodic comets, a mode of accumulation of absorbed energy from galactic cosmic rays will ensue.

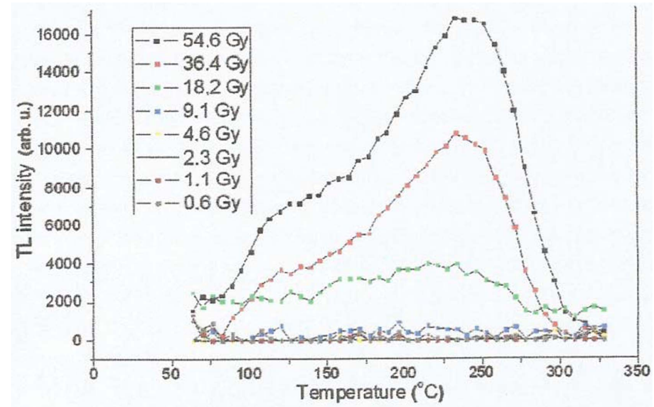

Figure 4. Thermoluminescent glow curve of CVD diamond samples exposed to 0.6–55 Gy gamma irradiation doses (Karczmarska et al. 2012).

In the work by Blair & Edgington (1970), samples of the lunar material delivered by Apollo 11 were investigated. Thermoluminescence of these lunar samples was excited by bombardment of protons with 159 MeV energy in the temperature range from −50°C to −200°C. At low temperature, the blue thermoluminescene of the pyroxene and the plagioclase factions was fixed. The thermoluminescent efficiency of the above-indicated fractions was moderate. For instance, the thermoluminescent efficiency of the pyroxene fraction at −135°C was equal to 4.09×10^{-6}. Figure 5 shows the glow curve of thermoluminescence of the pyroxene fraction that belonged to the lunar rock. After the first irradiation, the pale pyroxene fraction demonstrates a bright thermoluminescent flare, whereas the second irradiation did not cause thermoluminescence in pyroxene (smoothed curve on Figure 5). The astrophysical importance of these results is also rather high. The cometary mineral halos (or the mineral dust fluxes), presumably consisting of the minerals of pyroxene, can demonstrate the blue thermoluminescence flares at low temperatures. It is necessary to take into consideration that the moderate efficiency of thermofluorescence in the laboratory conditions may be related to a number of specific factors, including the fact that, in the given case, the pale pyroxene

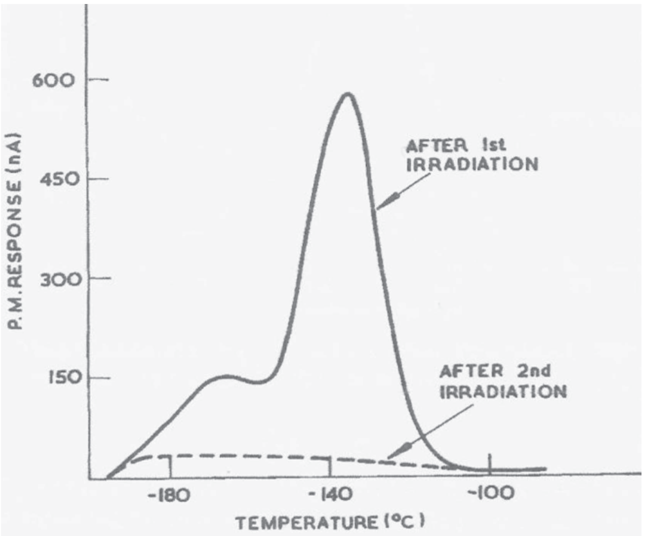

Figure 5. Thermoluminescent glow curves of pale pyroxene fraction, in the range 435–485 nm (Blair & Edgington 1970).

comprises a small part of the lunar samples' substance. Dust of the cometary halo, probably comprised of the pyroxene itself, can demonstrate considerably higher efficiency, taking into account the fact that thermoluminescence may be a characterizing feature of not only single mineral particles, but of a halo, as an array of the different-dispersed dust, in general.

At heliocentric distances $r < 2$ a.e. solar radiation, including solar energetic particles (SEP), may cause thermoluminescent flares in the mineral halos of comets. These flares may correlate with cyclical activity of the Sun, in response to powerful solar flares and other non-stationary processes.

The rapid thermoluminescent flares of cometary halos may differ according to their photometric and spectral features. They can be fixed in the B and R areas and occur spectrally in the form of wide bands of emissions of an appropriate profile within the ranges 4100–4800 Å and 6000–7500 Å.

The rapid nature of cometary flares and their belonging to the B or R bands are significant indicators of the thermoluminescent nature of given phenomena. Thus, the photometric and spectral data indicate (1) the speed of the phenomenon, (2) whether the flare belongs to the B or R spectral ranges, and (3) the appearance of the shortwavelength and long-wavelength short-lived emissions in the spectra that enable us to identify the thermoluminescent nature of the phenomenon. The above-mentioned features enable us to differentiate between the thermoluminescent flares and ordinary scattering by dust or the resonance fluorescence of gas.

We conducted a calculation of the ratio of the thermoluminescent flux $F_{\rm TL}$ to the flux of the scattered radiation $F_{\rm scat}$ for the dusty cometary halo, in accordance with the following baseline: heliocentric and geocentric distances of the comet $r = \Delta = 1$ au; halo radius $R = 500$ km; albedo of the halo dust particles A within the range 0.01–0.03; halo dust in the form of silicate crystalline microparticles and of organic composition; and ordinary flux of the solar radiation (electromagnetic and corpuscular).

According to Furetta (2003), the intensity of thermolumionecence $I_{\rm TL}$ of an elementary segment of a surface or an individual sample is defined as

$$I_{\rm TL} = \frac{E}{t} \tag{3}$$

where E is the energy of the exciting radiation and t is the process characterizing time. Thus, in the case of a dusty cometary halo (within the standard relation), the flux of thermoluminescence $F_{\rm TL}$ from the cometary halo will be expressed as

$$F_{\rm TL} = \frac{\pi R^2 I_{\rm TL}}{r^2}. \tag{4}$$

With the substitution of $I_{\rm TL}$ by $I_{\rm scat}$ in the numerator of relation (4), the flux of the solar radiation scattered by the same halo will be expressed by the same relation (4). Our calculations have shown that, for the case of albedo $A = 0.03$, the ratio $F_{\rm TL}/F_{\rm scat} = 3.3$. At the same time, duration of the thermoluminescence flare would be $\Delta t = 10''$. Moreover, in the case of albedo $A = 0.01$, $F_{\rm TL}/F_{\rm scat}$ could vary within the range 10–1.1, whereas the duration of the flares could vary within $\Delta t = 10''$–$90''$. In other words, in conditions of a rather low dust-particle albedo, the phenomenon the cometary halo dust thermoluminescence could be manifested in the form of bright thermoluminescent flares that weaken over time and become undetectable by ground instruments after the passage of $90''$. The ratio $F_{\rm TL}/F_{\rm scat} > 1$ proves that the thermoluminescent signal exceeds the scattered solar radiation. In addition, after the first bright phase of the flare and past $90''$ of the phenomenon's beginning, $F_{\rm TL}/F_{\rm scat} < 1$. We assess the corresponding phenomena for one astonomical unit, whereas for larger distances (e.g., $r = \Delta = 5$ a.e.) and assuming invariability of the chemical–mineralogical composition of the dust halo of a relevant comet, we can say that the $F_{\rm TL}/F_{\rm scat}$ ratio will have similar values. However, in cases of long geocentric cometary distances, detection by ground instruments would be difficult to some extent.

It seems necessary to add to our theoretical considerations the following important argument. The appearance of a significant gamma component during strong solar flares can strengthen dramatically both the brightness and duration of thermoluminescent flares of the cometary halo and the ratio $F_{\rm TL}/F_{\rm scat}$ may reach at a value of 20 or more. Despite this complex picture of the cometary halo thermoluminescent flare, we can assert confidently that the $F_{\rm TL}/F_{\rm scat}$ ratio for many cometary bodies may be higher than 1. Correspondingly, detection of this phenomenon by ground instruments will be possible without difficulties. The detailed parameters of thermoluminescent flares of comets can be determined on the basis of a series of observational experiments and analysis of archival data. Regardless of the above-considered laboratory results and the calculated values of the $F_{\rm TL}/F_{\rm scat}$ ratio, it should be underlined that the nature of thermoluminescence of the solid substance itself will precondition a release of the whole energy accumulated (over a long time period) in the form of optical radiation with a specific spectral composition.

Therefore, the cometary ices and dust, which accumulated the energy received from external sources over a long time period, will release it in the corresponding conditions in the form of bright optical flares.

4. DISCUSSION

In the present work, we have considered a possible process of thermoluminescence of cometary ices and dust. We have also demonstrated that the mineral and icy grains of the cometary halo, as well as the solid substance of the cometary nuclei, can accumulate the energy absorbed from external sources (e.g., solar radiation, galactic cosmic rays). When these cometary bodies approach the perihelion in conditions of increasing temperature of their substance, the accumulated energy may be released in the form of optical radiation of a flare nature. At the same time, the bright thermoluminescent flares will be characterized by relevant spectral features, namely the well-expressed emissions in the blue and red regions of the optical spectrum. We also considered the physical conditions necessary for the processes of accumulation, retention, and release of the energy by the cometary substances. We considered also the astrophysical projection of the results of laboratory experiments (which have been conducted in different periods) for studying the thermoluminescence of substances with different compositions and structures. In the works of Blair & Edgington (1970), Dalrymple & Doell (1970), Blair et al. (1972), Zinner (1980), and others, the results of investigation of thermouminescence of meteoric minerals and samples of cosmic substances, including lunar substance, are described. These results are valuable for a comparative analysis within the scope of the problem of cometary matter thermoluminescence. In particular, thermoluminescence of the organic component of meteroric substances may serve as a reference standard in the process of identifying short-lived, unknown cometary emissions. Spectral profiles of cometary halo luminescent emissions and the quenching law of such emissions will be an important "tool" for the understanding of luminescent sources in nature. In addition, a direct analogy or unambiguous explanation of the peculiarities of thermoluminescence of the cometary substance involving laboratory data regarding the meteoritic minerals and lunar samples can be inaccurate, due to peculiarities of the cometary substance, including the relict matter of the comets. The substance of the meteorites was placed into its branch of evolution of solar system small bodies, with further interaction with the Earth within the limits of the impact processes. As to the cometary substance, it has more initial nature with a lower level of processing and transforming. Therefore, the laboratory analogs themselves, within the scope of the discussed problem, must be chosen on the basis of specific criteria, including chemical–mineralogical simplicity of a sample; absence of a deformation of the crystal lattice of the microsample substance; samples that have not been exposed to ionizing radiation for a long period of time, etc. In other words, for a laboratory modeling of possible thermoluminescence of cometary ices and dust, conditions maximally similar to the cosmic ones should be created and corresponding materials selected.

We have shown that the solar radiation flux is sufficient to excite cometary substance thermoluminescence at different heliocentric distances, including $r \geqslant 5$ a.e. However, detectability of the thermoluminescence by ground instruments will depend on specific conditions; in particular, the thermoluminescent efficiency of mineral grains in a specific cometary halo. Thermoluminesence of cometary substances may be excited by both solar wind and the SEP. In the latter case, the thermoluminescent flares' brightness will be considerably higher, and the heliocentric distances at which they may take place is longer. Excitation of thermoluminescence from the cometary ices and dust by galactic cosmic rays may be of a longer duration, showing the well-expressed phases of accumulation and preservation of the absorbed energy. At the same time, the process of accumulation will be most efficient near the aphelion region of the cometary orbit. Owing to the physical properties and the chemical–mineralogical composition of the cometary nuclear substance, as well as to the general rule that cometary nuclei near the aphelion region do not have an expressed atmosphere, no less than 70%–80% of the delivered energy of galactic cosmic rays can be accumulated by the inner layers of the nucleus before being released in the form of optical flares as that comet approaches even closer to the Sun.

The icy and mineral components of the cometary nuclei may contain radioactive isotopes—sources of radiation, potentially accumulated by the surrounding regions and layers of the nuclear substances.

The radioactive isotopes that may exist in cometary nuclei include ^{40}K, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{14}C. Thus, the energy accumulated by the cometary substance over millions of years may be released in the form of thermoluminescent optical flares if the substance is heated up to a certain temperature. However, observability of such phenomena by ground instruments is another issue requiring special investigation. Not every fragment of a nucleus and its related arrays of dust matter will contain a sufficient quantity of the radioactive isotopes or accumulate sufficient energy (for ground detection) during the period of these isotopes' half-lives.

Returning to chemical–mineralogical properties of the cometary dust halo, it seems necessary to indicate that the most probable candidates to be carriers of the accumulated energy, i.e., the sources of thermoluminescent flares, would be the differently dispersed mineral particles and icy grains, as well as the dust particles with mixed compositions of nucleii and mantles. Silicate nano- and microparticles and the frozen hydrocarbon particles (FHP, PAHs in *n*-alkanes) may belong to this group, in particular. The mineral dust particles of the cometary halo that exist in a crystalline state will demonstrate a bright thermolunimescence, whereas amorphous particles will not exhibit thermoluminescent properties.

Another noticeable factor is the existence of different impurities in the crystal lattice of the nano- and microdust. These impurities alone will certainly be responsible for the spectral peculiarities of thermoluminescent dust, and, in some cases—for extinction of the thermoluminescence, for instance, in the case of iron ions being present in the dust substance.

In the second half of the last century, thermoluminescence was proposed as an explanation of temporary optical phenomena on the surface of the Moon (Sun & Gonzalez 1966). Considerable studies were conducted to explain these phenomena, in particular, thermoluminescence of lunar samples, meterorites, and various minerals were studied. However, a direct analogy between possible thermoluminescence of the cometary substance and that of lunar samples, or a certain extrapolation of the results of investigation of the lunar samples, which could be applied to cometary substances, does not seem quite justified due to the reasons given below: (1) difference between the chemical–mineralogical composition of the cometary substances and the composition of the lunar rocks; (2) a certain transformation of the chemical–mineralogical features of the lunar rocks' substance due to the impact processes (bombardment by meteorites) that took place over a long period of time; (3) spatial location of the Moon, characterized by certain peculiarities including the relatively lower variation of its heliocentric distance, as well as its synchronous rotation. Taking into consideration the above three factors, we may conclude that the primary properties of the lunar substance, including the property of thermoluminescence, could have been lost long ago, or weakened due to the above-indicated physical circumstances. It cannot be excluded that the lunar rock samples have retained residual thermoluminescence. On the contrary, cometary bodies moving in elliptical orbits and emitting significant portions of relict substance can characterized by bright thermoluminescence. Generally, the comets' nuclei may be the sources of the chemically pure dust matter in the form of fluxes of the differently dispersed particles. For example, sodium dust may create dusty shells of different diameters and density that form anomalous and ordinary cometary tails. In conditions of dramatically increased temperature or influence by other external factors, extended structures (i.e., tails) of the sodium dust of comets can demonstrate bright thermoluminescence of a relevant spectral composition.

Turning to our main conclusion on the basis of the aforementioned, we may conclude that thermoluminescence of solid cometary matter may be a quite common physical phenomenon characterizing periodic and non-periodic comets that can be detected well by advanced optical ground instruments. Detection and research of thermoluminescence of solid cometary substances may become an effective tool for revealing the cometary relict substance; this direction of cometary research may be named "luminescent relictography." In other words, it would consist of obtaining cometary images (at the time of flares/outbursts) in bands of relict substances' luminescent radiation. Instruments with a large aperture and sufficient spectral resolution should be applied at that time. As an initial stage of such investigation, the following common strategy seems advisable: (1) spectral and photometric observations of a comet characterized by flaring activity; (2) searching for and collecting archival data concerning the spectra of cometary flares; and (3) identification of the cometary substance (the source of thermoluminescent flares) on the basis of comparative analysis. The main result of such an investigation could be the determination of the basic properties of solid cometary relict substances. It would be advisable to create a spectral atlas of cometary flares on the basis of their fragmented spectral materials (photographic plates, CCD images, registrograms, etc.) kept (mainly unpublished) at the archives of different observatories and centers. Thus, we propose our theoretical justification: achieving a deeper understanding of the above-considered phenomena should proceed toward practical studies, one goal of which would be understanding the formation and evolution of comets and the other small bodies in our solar system.

5. CONCLUSION

Cool cometary dust accumulating the absorbed energy of hard electromagnetic and corpuscular radiation plays an important role in the evolution of our solar system. Cool cometary dust existing below the horizon of accumulation retains absorbed energy for a long period of time. The "frozen" phosphorescence of those cometary dust particles can serve as the key to solve a number of astrophysical and cosmogonical problems.

Thermoluminescence of the silicate and organic dusts of comets in the form of mineral and icy grains may become a reliable source of information about the history of cometary matter and other icy bodies of the solar system. We have described a possible phenomenon of cometary substance thermoluminescence in general on the basis of the contemporary ideas, results of observations, and laboratory experiments. There are many other issues and challenges that need to be addressed, which can be achieved on the basis of new experiments and broad scientific discussion.

REFERENCES

Benoit, P. H., & Sears, D. W. G. 2001, in 32nd Annual Lunar and Planetary Science Conf. Abstract no. 1795
Blair, I. M., & Edgington, J. A. 1970, in Proc. Apollo 11 Lunar Science Conf., Vol. 3, Physical Properties, Geochimica et Cosmochimica Acta Supplement, ed. A. A. Levinson (New York: Pergammon), 2001
Blair, I. M., Edgington, J. A., Chen, R., & Jahn, R. A. 1972, in Proc. of the Third Lunar Science Conf. Vol. 3, Geochimica et Cosmochimica. Acta Suppl, 2949
Bobrovnikoff, N. T. 1927a, ApJ, 66, 145
Bobrovnikoff, N. T. 1927b, ApJ, 66, 439
Churyumov, K. I., Kleshchenok, V. V., & Vlassyuk, V. V. 1997, EM&P, 78, 111
Dalrymple, G. B., & Doell, R. R. 1970, in Proc. Apollo 11 Lunar Science Conf., Vol. 3, Physical Properties, Geochimica et Cosmochimica Acta Supplement, ed. A. A. Levinson, (New York: Pergammon), 2081
Duley, W. W., Seahra, S., & Williams, D. A. 1997, APJ, 484, 866
Durrani, S. A., & Christodoulides, C. 1969, Natur, 223, 1219
Furetta, C. 2003, Handbook of Thermoluminescence (Singapore: World Scientific)
Gucsik, A., Endo, T., Nishido, H., et al. 2013, M&PS, 48, 2577
Karczmarska, A., Mitura-Nowak, M., Nowak, T., & Marszalek, M. 2012, Acta Phys. Polonica A, 121, 510
Koike, C., Chihara, H., Koike, K., et al. 2002a, M&PS, 37, 1591
Koike, K., Nakagawa, M., Koike, C., et al. 2006, P&SS, 54, 325
Koike, K., Nakagawa, M., Koike, C., Okada, M., & Chihara, H. 2002b, A&A, 390, 1133
Pringsheim, P. 1951, Fluorescence and Phosphorescence(Moscow: Inostr.Lit.)
Sears, D. W. G., Benoit, P. H., & Akridge, D. G. 1999, M&PSS, 34, A105
Simonia, I. 2007, Ap&SS, 312, 27
Simonia, I. 2011, AJ, 141, 56
Sinonia, I., & Simonia, T. 2004, in Proc. of Ceres 2001 Workshop, ed. J.-E. Arlot & W. Thuillot, 191
Sun, K. H., & Gonzalez, J. L. 1966, Natur, 212, 23
Witt, A. N., & Vijh, N. P. 2004, in ASP Conf. Proc. 309, Astrophysics of Dust, ed. A. N. Witt, C. C. Clayton, & B. T. Draine, (San Francisco, CA: ASP), 115
Zinner, E. 1980, in Proc. Conf., The Ancient Sun: Fossil Record in the Earth, Moon and Meteorites, ed. R. O. Pepin, J. A. Eddy, & R. B. Merrill (New York and Oxford: Pergamon), 201