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Photoluminescence and Cathodoluminescence by Cosmic Dust

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Abstract—The photoluminescence and possible cathodoluminescence of cosmic dust is considered. It is shown that the dust of planetary nebulae can luminesce under the action of fluxes of charged particles. The results of a comparative analysis of unidentified emission features in the optical spectrum of the nebula NGC 7027 and the luminescence emission of a number of minerals is presented. It is shown that the dust in this nebula includes diamond grains.

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1. INTRODUCTION

The question of the luminescence of cosmic dust has recently become topical, stimulated by the detection of extended red emission at 5400–9400 Å in the spectra of reflection nebulae, protoplanetary nebulae, and other Galactic objects [1–3]. In [4, 5], this red emission is interpreted as photoluminescence by the cosmic dust contained in these objects, and some mechanisms associated with this luminescence are described together with its expected behavior. Models for the dust grains that are supposed to be responsible for this extended red emission in reflection and protoplanetary nebulae have also been developed. In one model, the dust grains have the form of microscopically amorphous grains of carbon enriched in hydrogen [4, 5]. Such grains luminesce intensely in a broad, structureless band at 5400–9400 Å under the action of UV radiation. It was shown in [6, 7] that crystalline silicon grains with nanometer sizes also luminesce intensely in this same band under the action of UV radiation. It is proposed in [8] that a broad, structureless band of emission at these wavelengths could represent thermoluminescence of silicate particles. Discussions of such mechanisms are ongoing. There also exist other phenomena that can be interpreted as luminescence by cosmic dust. It was proposed in [9] that unidentified emission lines in cometary spectra may represent luminescence by frozen hydrocarbon particles in the icy halos of the comets.

Photoluminescence by solid cosmic material carries information about its chemical and minerological composition, crystalline structure, temperature, and other properties. This information can be extracted via a comparative and mutually supplementary analysis of astronomical, physicominerological, photochemical, and other data. Objects whose dust component can luminesce intensely under the action of UV radiation include (1) reflection and planetary nebulae, (2) peculiar objects such as the "Red Rectangle" and circumstellar disks, and (3) interstellar dust. Micron and nanometer grains made of (a) carbonaceous dust, (b) silicon dust, (c) frozen hydrocarbon particles, and (d) material with small amounts of admixtures can all luminesce. The UV radiation from stars is absorbed by dusty material and then reradiated in the optical, with $E_{\rm abs} > E_{\rm rad}$. The absorbed energy goes into atomic transitions to excited states. The return of the excited electrons to the ground state is accompanied by the emission of lower-energy photons (except for the case of radiationless transitions in heated matter). This standard photoluminescent process is realized at certain modest distances from the source of excitation—a star. This distance varies, depending on the spectral type of the star, density of the circumstellar dust, etc. However, the possibility of random processes, when individual high-energy UV photons give rise to photoluminescence by scattered grains in the interstellar medium, cannot be ruled out. The intensity of photoluminescence by grains depends on the energy of the exciting radiation. The photoluminescence spectrum of cosmic dust is determined by its chemicominerological composition.

2. THE POSSIBLE VARIETY OF PHOTOLUMINESCENCE OF DUST

Photoluminescence by cosmic dust has thus far been detected via (a) extended red emission and (b) the emission of frozen hydrocarbon particles in the icy halos of comets. We will suppose that variety in the chemicomineralogical composition of Galactic dust determines the variety of photoluminescence spectra observed. Photoluminescence by matter in the objects listed above should be characterized by certain properties: its spectral composition, intensity, afterglow period, decay curve, etc. Unambiguous identification of such properties can lead to identification of the types of grains present in the material comprising a given type of object. The photoluminescence spectrum of cosmic dust can have the form of (1) a set of individual emission lines in the corresponding part of the spectrum, (2) a series of lines or group of series in the optical and infrared, (3) a continuum or broad, structureless band in the optical or infrared, and (4) a complex profile—individual narrow emission lines against the background of a broad, structureless band. This fourth possibility will be the case for grains with a complex chemicomineralogical compsition—the polycrystalline structures of mineral intrusions, etc. The temperature of the dust will appreciably influence the spectrum of its photoluminescence. For example, frozen organic mixtures can have quasi-line photoluminescence spectra at $T = 77$ K and broad, structureless emission at $T > 100$ K [9]. The chemicomineralogical composition and certain other characteristics of the dust will determine the quantum yield of the photoluminescence. The quantum yield of organic grains can vary in the range 10–30%, while the quantum yield of organic grains (including frozen mixtures) can vary in the range 50–90% [10]. This last circumstance is important, particularly in connection with the detection of photoluminescence by cosmic dust, since this will be much easier in the case of a high quantum yield. We believe that luminescence by nanometer grains carries information about the “structural material” of the star. Luminescence by dust grains (particles microns or larger in size) carries information about the evolution of the matter during the formation of planetary systems. It was shown in [11] that frozen oxygen and nitrogen luminesce intensely under the action of UV radiation.

We believe that an analogous process can occur in a cosmic medium when grains with oxygen or nitrogen mantles are located in a hard radiation field at a temperature of 50–65 K.

An important aspect of the problem is the stability of the luminescence properties of cosmic dust. When the grains are located in a UV radiation field for a long time, they can totally or partially lose their ability to luminesce, due to the photoreconstruction of their surface layers. Therefore, we suppose that relatively old grains of various Galactic objects can luminesce only with a low quantum yield, which, in turn, hinders detection of the corresponding luminescence signal. On the other hand, the condensation of new mantles of the grains or enrichment the mantles in certain admixtures (such as organic molecules) can establish or renew the luminescence properties of the grains.

Observations have concentrated mainly on the detected extended red emission from reflection nebulae and other objects. The low success of searches for grain photoluminescence at 4000–5000 Å may be due to the relatively low quantum yield of grain photoluminescence at these wavelengths. However, the fact that grains luminesce in the blue more weakly than in the red does not remove the topical nature of the problem, and the question of photoluminescence by dust at short wavelengths should be investigated. Our hypotheses need to be verified using observational data. We cannot rule out the possibility that, in a number of cases, out-of-atmosphere observations will be required for the detection of weak photoluminescence by cosmic dust.

3. THE POSSIBILITY OF CATHODOLUMINESCENCE BY DUST PARTICLES

We propose that cathodoluminescence of cosmic dust is also possible. Stars as sources of radiation also act on dust through fluxes of charged particles—electrons and protons with various energies. The bombarding of dust grains by beams of electrons and/or protons could lead to cathodoluminescence of these grains. In this case, 90% of the absorbed energy of the charged particles will go into heating the grains, while the remaining 10% goes into exciting cathodoluminescence and secondary electron emission. The elementary process could have the character of absorbing the supplied energy at all nodes of the crystal lattice of the dust grains and transfering the absorbed energy to luminescence centers. Matter with an amorphous structure in which the transfer of absorbed energy is weak will be characterized by weak cathodoluminescence. Crystalline dust grains in interstellar or circumstellar clouds can luminesce intensely under the action of fluxes of charged particles. Cathodoluminescence of amorphous grains will be weak or completely absent. In general, the strength of cathodoluminescence by grains will be determined by the energy of the bombarding electrons and the current density in the particle beam. Under the conditions in cosmic medium, dust grains of various sizes and chemical compositions can be enriched by admixtures of ions when the grains are located for some time in fluxes of ions such as Cu^+, Mn^+, Na^+, and also C^+, N^+, O^+, and others. To better understand the cathodoluminescence of cosmic dust, we must adapt the results of laboratory studies of cathodoluminescence of the corresponding material. Together with an analysis of available laboratory data, modeling of cathodoluminescence by analogs of cosmic dust could be useful.

It was shown in [12] that “the excitation of luminescence via electron bombardment has much in common with excitation by short-wavelength light and beams of α particles. Transfer of energy in a crystal from the place of absorption to the radiating atoms is apparently carried out by resonance phenomena. For example, silicates are characterized by a very sharp fall in the light output as the size of the grains is reduced to fractions of a micron, when the transverse size of the crystal coincides with or becomes smaller than the depth to which the electrons penetrate into the material.” In the case of silicate cosmic dust, this means that the intensity of cathodoluminescence by nanometer grains will be low, while the intensity of cathodoluminescence by micron grains will be appreciably higher.

In [13], we presented a formula for calculating the intensity of cathodoluminescence by surfaces of asteroids and other small bodies. For the case of circumstellar dust, this formula will take the form

$$I = \frac{lps\int\limits_{E_1}^{E_2} zdz}{r^2}, \quad (1)$$

where l is the quantum yield of cathodoluminescence for the given material, p the current density in the beam in particles cm^{-2} s^{-1}, s the area of a segment of the dust cloud visible from the Earth, z the energy of a charged particle in ergs, with $E_2 > z > E_1$, and r the distance to the dust cloud in cm.

The detected cathodoluminescence signal will depend on the energy of the charged particles bombarding the dust, distance to the object, quantum yield of the cathodoluminescence, sensitivity of the receiver, and ratio of the flux of luminescent radiation to the flux of scattered thermal radiation from the irradiating star. This ratio can be calculated based on absolute spectrophotometry data.

4. POSSIBLE CATHODOLUMINESCENCE BY DUST IN PLANETARY NEBULAE

Planetary nebulae are one type of object whose dust can luminesce under the action of fluxes of charged particles. It was shown in [14] that the dust in many planetary nebulae could be fairly cool, with temperatures of 70–150 K. It is also noted in [14] that the spatial distribution of dust in planetary nebulae could be uniform. These facts are important for our analysis, since hot dust will not display well defined cathodoluminescence properties. Cool, isotropically scattered dust will luminesce under the action of fluxes of charged particles. This luminescence will be manifested as an additional contribution to the emission of the nebula.

In our view, in general, the cathodoluminescence of dust in planetary nebulae can be expected to have the following character. Collisions between free electrons and cool dust grains will excite cathodoluminescence of the grains in the optical, in the form of individual narrow lines or extended, structureless bands. The luminescent centers of a grain crystalline lattice will emit excess energy in the optical over a characteristic time t. The intensity of the dust cathodoluminescence will depend primarily on the energy of the bombarding electrons. The spectral composition of this cathodoluminescence will be determined by the chemicominerological composition of the dust grains, the presence of admixtures of ions of various types, and other factors. In laboratory samples of crystalline material, their ability to cathodoluminesce under the action of beams of electrons is limited to a fairly short time. The same should be true of cosmic dust, including dust in planetary nebulae. However, if dust grains are formed near the nebula's core and are then spread throughout the nebula, the overall process of dust cathodoluminescence will either be constant or will periodically recur. The detection of dust cathodoluminescence from a planetary nebula would make it possible to (a) establish the chemicomineralogical composition of the dust, (b) determine the type of crystalline lattice in the dust grains, (c) establish what types of ion admixtures are present, (d) determine the temperature of the dust, and (e) determine the energy of the electrons and protons exciting the cathodoluminescence. The cathodoluminescence spectra for planetary nebulae currently available resemble a set of weak, unidentified emission lines. Our description of the cathodoluminescence of dust in planetary nebulae will be valid for relatively cool dust.

5. LUMINESCENCE BY DUST IN THE NEBULA NGC 7027

In order to reveal luminescence by dust in planetary nebulae, we compared the positions of unidentified emission lines in the spectrum of the nebula NGC 7027 with the positions of the main emission features in the luminescence spectra of various minerals. We selected NGC 7027 for this study for two reasons: (i) the brightness of the nebula and (2) the presence of extended red emission of dust [15].

As laboratory material for the comparison, we used the catalog of cathodoluminescence and photoluminescence emission lines for a number of minerals [12, 16, 17]. A study of NGC 7027 in the optical is described in [18], including identification of various emission lines and investigation of their nature. The identified emission lines belong to the ions CII, CIV, OIII, OIV, SiII, SiIV, NIV, NeIII, NeIV, HeII, MgII, MgV, MnIV, MnV, FeIII, FeV, and others. However, it was not possible to identify all the observed emission features; 55 emission lines of NGC 7027 remained unidentified. It is precisely these emission lines that are the objects of our comparison.

The results of our analysis are as follows. The columns below present the wavelengths of unidentified emission lines of NGC 7027 from [18], the wavelengths of the luminescence emission lines of the corresponding mineral (diamond dust), the temperature at which the luminescence from the mineral was emitted, and a reference:

4261.9 Å	4263 Å	83 K	[17]
4638.9 Å	4638 Å	83 K	[17]
5029.6 Å	5030 Å	77 K	[16]
5772.6 Å	5773 Å	77 K	[16]
5780.5 Å	5780 Å	77 K	[16]

We carried out our comparison with an accuracy of ±1.2 Å. We were able to identify 9% of the previously unidentified emission lines in the spectrum of NGC 7027 as being due to photoluminescence by dust. Our analysis indicates that the dusty material in NGC 7027 includes diamond dust that luminesces under the action of UV radiation.

The presence of diamond dust grains in NGC 7027 is very probable, since this object is known to be rich in carbon [15]. Note that the data taken from [16] refer to photoluminescence by diamond. However, we must take into account the fact, confirmed in the laboratory, that photoluminescence excited by hard UV radiation and cathodoluminescence excited by fluxes of high-energy electrons are essentially identical phenomena, which differ only in the means of supplying energy to the material in question [12]. Our analysis indicates that diamond mineral that luminesces in the optical is often enriched in nitrogen atoms.

Thus, our analysis has enabled us to, first, establish the chemicomineralogical composition of the dust (or of a component of this dust) in the nebula NGC 7027 and, second, establish the mean temperature of the dusty material ($T = 79$ K). At the same time, we were not able to identify cathodoluminescent emission lines in the spectrum of NGC 7027. We also conclude based on our analysis that only a small fraction of the unidentified emission lines in the spectra of planetary nebulae are associated with photoluminescence by dust. The remaining large number of unidentified emission lines may be due to fluorescence of the gaseous component of the nebulae. The detection of photoluminescence by dust in NGC 7027 was possible first and foremost due to the quantum yield of the photoluminescence, which was fairly high at the low temperatures of the dust. The possible presence of diamond grains in circumstellar dust is discussed in [19, 20], where it is concluded that the probability for this is high. This, in turn, represents a strong argument in support of our results.

We also note that the intensity and spectral composition of photoluminescence by dust in planetary nebulae can probably change in time during the evolution of the nebulae.

6. CONCLUSIONS

We have described certain important properties of photoluminescence and possible cathodoluminescence of cosmic dust in planetary, protoplanetary, and reflection nebulae, as well as other objects. Given the similarity of the processes of photoluminescence excited by hard UV radiation and cathodoluminescence excited by fast electrons, we conclude that these processes can lead to the appearance of similar emission lines in the spectra of these cosmic objects. The problem of the extended red emission of reflection, planetary, and protoplanetary nebulae remains unresolved in terms of establishing the chemical composition of the dust responsible for this emisson. There is no doubt that this extended red emission represents photoluminescence by dust. However, due to the similarity of the processes of photo- and cathodoluminescence, generally speaking, we expect that such red emission could also be excited by fluxes of fast electrons and protons, although the quantum yield of cathodoluminescence could be fairly low in many cases (for many materials).

Given the variety of the chemicomineralogical composition of cosmic dust and of the conditions exciting luminescence, we expect variety in the luminescence spectra of cosmic dust as well, in terms of both the spectral composition and the intensity distribution. However, the problem of detecting this luminescence remains a complex instrumental task. We propose that a number of previously unidentified emission lines in the planetary nebula NGC 7027 represent photoluminescence by diamond dust in this nebula.

Our comparative analysis has enabled us to determine the chemical composition of the dust in this nebula and identify a number of previously unidentified emission lines.

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