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FROZEN HYDROCARBON PARTICLES AS A LUMINESCENT DUST COMPONENT OF NEBULAR MATTER

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This paper is a continued examination of luminescence of cosmic dust, in particular the dust in reflecting nebulae. A model of frozen hydrocarbon particles in the form of a nucleus with a polycrystalline mantle is proposed. The basic properties of these particles, as well as the technique for obtaining spectra of the nebula CED 201 on the 2 meter TLS telescope with a Naismith focus spectrograph, are described. Part of the detected unknown emission in the spectrum of CED 201 is identified as photoluminescence of frozen hydrocarbon particles that form part of the dust component of the nebular matter.

Keywords: *(ISM): reflection nebulae - individual: CED 201*

1. Introduction

In recent years a number of researchers have proposed different models for the dust particles that might constitute the basis of interstellar and circumstellar dusty matter. Some of the models are based on laboratory studies, while others are theoretical models that invoke data from astronomical observations [1-5]. After the extended red emission from reflecting nebulae was interpreted as photoluminescence of their dust, a discussion developed regarding the physical properties and chemical composition of the dust particles responsible for this emission.

The extended red emission in the spectra of reflecting nebulae is a structureless band over the range 5400-9400 Å. A model description of the dust particles, the sources of this emission has been proposed [6]. In this model each individual dust particle is a carbon grains that is enriched in hydrogen. Under UV irradiation a dust particle of this sort is capable of luminescing within this spectral range. In nature there are other chemical elements and compounds that exist in various states of aggregation and under various temperature and pressure conditions, and are capable of luminescence in the form of broad band emission. Thus, other models, in particular a model involving silicon nanoparticles [7], have been proposed taking account of the distribution of the relevant elements and compounds. There it was shown, in particular, that under laboratory conditions crystalline silicon particles of nanometer dimensions irradiated with UV radiation will

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produce broad band luminescence similar to that observed in reflecting nebulae. However, in conducting laboratory experiments and creating theoretical models and concepts, it is necessary to bring the modelled conditions closer to natural conditions, given the extensive abundance of a whole series of compounds in the universe. Thus, often the experiments have been done at room temperature, while the actual temperature of the dust in nebulae maybe entirely different. This is especially important when the quantum yield of luminescence is elevated at low temperatures. Insufficient attention has been paid of the luminescence of frozen polycyclic aromatic hydrocarbons in the past. Thus, we propose a new model for the dust particles of reflecting nebulae and other objects following our discovery of isolated, quite narrow luminescence emission in the spectrum of the nebula CED 201 [8].

2. Model of frozen hydrocarbon particles: nucleus - polycrystalline mantle

Assuming that an interstellar gas cloud contains finely dispersed solid carbonaceous particles and that the cloud is composed of a mixture of polycyclic aromatic hydrocarbons and acyclic hydrocarbons, then at some time t the cooling of the gaseous mixture leads to the onset of condensation onto the carbonaceous particles. The Clausius-Clapeyron equation will apply to this phase transition.

On further cooling the condensate formed on the carbonaceous dust particles crystallizes to form a polycrystalline mantle. Thus, more complex dust particles are formed as a result of cooling; these consist of a nucleus of carbonaceous particles and a polycrystalline mantle made up of polycyclic aromatic and acyclic hydrocarbons. Complex particles of this sort will be found in a frozen state near $T \approx 77$ K. We propose referring this kind of complex dust particle as frozen hydrocarbon particles.

A frozen hydrocarbon particle model has been proposed before [9], but without a central carbonaceous particle-nucleus. Here, on the other hand, we regard the nucleus-polycrystalline mantle model as a more complex particle, the next stage in the hierarchy of frozen hydrocarbon particles. The validity of this approach seems evident, since frozen hydrocarbon particles can be formed under various conditions, in particular, when condensation nuclei are either present or absent. In the model of Ref. 9, the frozen hydrocarbon particle is an ice dust particle in a cometary atmosphere, while in terms of the nucleus-polycrystalline mantle model the frozen hydrocarbon particle is a complex dust particle which forms part of the dust in reflecting nebulae and other objects in the galaxy. In the following we shall consider frozen hydrocarbon particles with a nucleus-polycrystalline mantle structure. We believe that the duration of the process whereby the frozen hydrocarbon particles are formed can vary and will depend on a number of parameters, including: the chemical composition of the gas mixture, the temperature of the medium, the concentration of carbonaceous particles, etc. Each individual frozen hydrocarbon particle will have its characteristic diameter and mass. The characteristic lifetime of the frozen hydrocarbon particles will vary, depending on the specific chemical composition of the polycrystalline mantle and the temperature of the particle. If the mantle of a given particle contains components such as n-hexane, a sharp rise in the temperature of the particle will lead to deterioration of the polycrystalline mantle and only the aromatic constituent will remain in it [8].

We assume that interesting effects will occur when frozen hydrocarbon particles interact with short wavelength radiation. In particular, dense clouds consisting of frozen hydrocarbon particles embedded in a gaseous substant may cause interstellar absorption in the UV and optical ranges. The absorbed energy will be partially reradiated in the visible by the matter in the mantle of the frozen hydrocarbon particles; that is, photoluminescence will take place. Prolonged exposure of the frozen hydrocarbon particles to UV radiation will cause them to evolve photochemically. When frozen hydrocarbon particles are acted on by fast protons for an extended period, part of the energy of these charged particles may be accumulated by molecules in the polycrystalline mantle; this will show up in the form of molecules in metastable energy states. Until heating or collisional impact on the frozen hydrocarbon particles, these act as quasireservoirs of accumulated energy. These external interactions are followed by emission of the excess energy from the frozen hydrocarbon particles in the appropriate ranges, possibly in the form of broad structureless emissions (thermoluminescence). Similar phenomena, but involving the thermoluminescence of silicates, have been studied under laboratory conditions [10,11]. Frozen hydrocarbon particles may be present in various objects in the galaxy: dust complexes, reflecting nebulae, circumstellar dust disks, and other objects that are rich in dust. Frozen mixtures with a chemical composition analogous to that of the polycrystalline mantles of frozen hydrocarbon particles have been obtained in the laboratory [12].

The main feature of the photoluminescence spectra of these analogs was their quasilinearity. Frozen hydrocarbon particles with natural polycrystalline mantles may also be characterized by quasilinear photoluminescence spectra. Photoluminescence signals from frozen hydrocarbon particles are detectable because the mantle of frozen hydrocarbon particles contains polycyclic aromatic hydrocarbons, which have a high photoluminescence quantum yield (50% or more [13]).

3. The nebula CED 201: observations and data processing

There are several techniques for identifying the photoluminescence of reflecting nebulae, protoplanetary peculiar nebulae, and other objects. These methods include (1) the standard method of dividing the nebula spectrum by the spectrum of the illuminating star and (2) analyzing the depth of absorption of the nebula and the illuminating star [13]. These techniques are currently used for discovering the extended red emission of reflecting nebulae and other objects in the range 5400-9400 Å [13-15].

In order to detect the luminescence of the dusty matter in the nebula CED 201 we have made spectroscopic observations of this object on the 2 meter TLS telescope (Germany) in the range from 4000-9000 Å using a Nasmyth focus

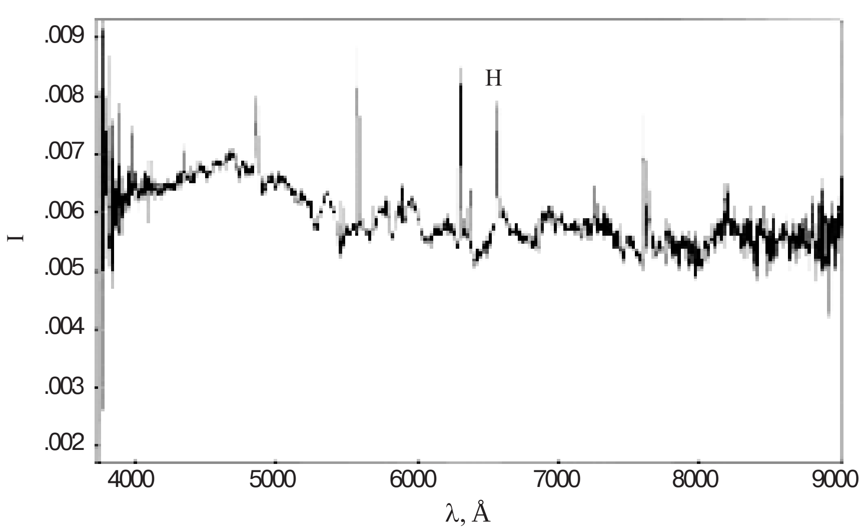

Fig. 1. Spectrum of CED 201, 4000-9000 Å

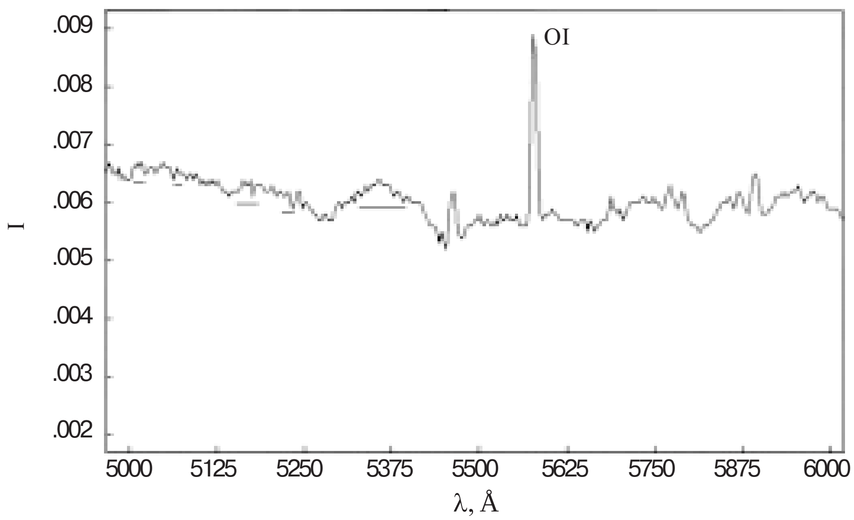

Fig. 2. A fragment of the spectrum of CED 201, 5000-6000 Å. The horizontal lines indicate the identified luminescence emission features.

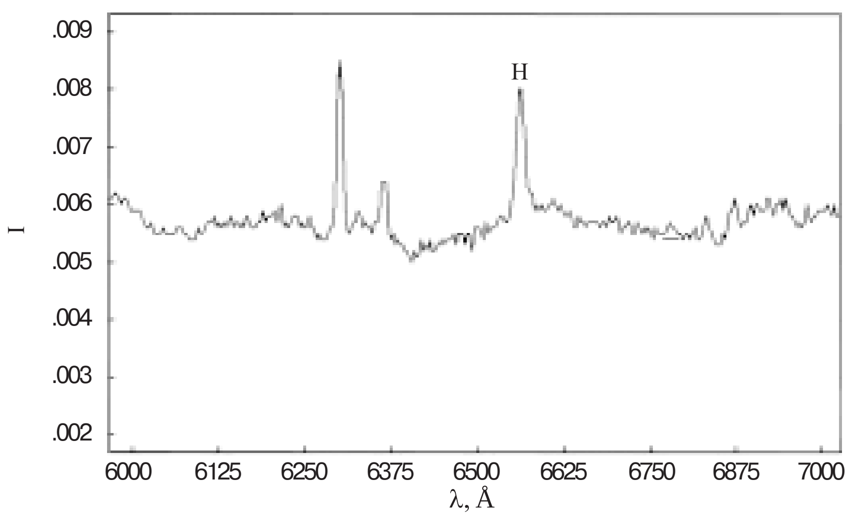

Fig. 3. A fragment of the spectrum of CED 201, 6000-7000 Å. The horizontal line indicates one of the emission features that remains unidentified.

prism spectrograph. The average dispersion of the spectrograph was 225 Å/mm. The maximum slit lenght was 3.24 arc min. The detector was an 800×2024 CCD. Spectra of the reflecting nebula CED 201 and the illuminating star BD+69°1231 were obtained. In particular, spectra of the bright region of the nebula (away from the star) and of the illuminating star were obtained. The exposure times were 600 s for the nebula and 300 s for the illuminating star.

Standard operations of extracting the spectra, filtering of cosmic background particles, flat fielding, calibration, etc., were carried out. The spectrum of the night sky was subtracted from that of the nebula and the resulting spectrum was divided by the spectrum of the illuminating star. The resulting spectrum is shown in Figs. 1-3. This spectrum was processed using the program package DECH 20T of the Special Astrophysical Observatory of the Russian Academy of Sciences.

4. Interpretation

The resultant spectrum was compared with standard comparison spectra: the spectrum of the night sky, a set of forbidden emission features, the spectrum of planetary nebulae, the spectrum of B-type stars, emission from artificial Hg and Na sources, hydroxyl emission, etc. The comparison was done with a precision of ±1Å. After comparison, on eliminating the corresponding bands from the complete emission set (more than 200 bands), there remained 11 previously unknown emission features that belonged to none of the known emission sources. These emission features are the following: 5001-5021; 5061-5081; 5156-5175; 5234-5245; 5315-5377; 6772-6788; 7589-7619; 8061-8067; 8079-8091; 8398-8408; 8711-8724 Å.

We decided to compare our unknown emission features with the luminescence emission of 100 aromatic molecules [12]. The corresponding data base contains the wavelengths of fluorescence and phosphorescence emission in the quasilinear spectra of polycyclic aromatic hydrocarbons and acyclic hydrocarbons which form a polycrystalline solution at 77 K. The results of our comparative analysis are given below.

The first column of Table 1 lists the wavelengths of some unknown emission features in the spectrum of CED 201; the second column, some polycyclic aromatic hydrocarbons and their chemical formulas (the solvent is n-hexane); and the third, the fluorescence and phosphorescence wavelengths of the corresponding polycrystalline solutions. The wavelengths are in Angstroms. It should be noted that the polycrystalline solutions of polycyclic aromatic hydrocarbons + acyclic hydrocarbons (e.g., phenanthrene + n-hexane) are chemical analogs of the material in frozen hydrocarbon particles.

We were able to identify five unknown emission features in the spectrum of CED 201 as photoluminescence of frozen hydrocarbon particles. The luminogens are polycyclic aromatic hydrocarbons such as 2,3 orthophenylenepyrene, tetracene, coronene, phenanthrene, chrysene, and 1,2 benzopyrene. In cases of reduced concentrations of the polycyclic aromatic hydrocarbons or higher temperatures, the quasilines in the fluorescence and phosphorescence spectra will undergo broadening. The widths of the luminescence bands in the spectrum of CED 201 indicate that the frozen luminescent material in the dust of this nebula has a temperature $T > 77$ K. The remaining 6 unknown emission features in the spectrum of CED 201 could not be identified by this comparison procedure. This may have happened for two reasons: (a) emission

TABLE 1. Results of the Comparative Analysis

λ, Å of the unknown feature	Name and formula of polycyclic aromatic hydrocarbons	λ, Å
5001-5021	2,3 Orthophenylenepyrene $C_{22}H_{12}$	5005
5061-5081	Tetracene $C_{18}H_{12}$	5073
5156-5175	Coronene $C_{24}H_{12}$	5159
5234-5245	Tetracene $C_{18}H_{12}$	5238
5315-5377	Phenanthrene $C_{14}H_{10}$	5327
	Chrysene $C_{18}H_{12}$	5318, 5358
	1,2 Benzopyrene $C_{20}H_{12}$	5349, 5366

features at wavelengths greater than 6700 Å belong to the extended red emission and (b) Teplitskaya's data base does not contain emission features lying beyond 6500 Å. Which of these reasons is basic remains to be established. A comparative analysis of the unknown emission features of the nebula CED 201 (Nasmyth focus) with the luminescence spectra of 300 minerals [16] showed that the sources of the unknown features in the spectrum of this nebula cannot be mineral particles of C and SiO_2.

Figure 1 shows the resultant spectrum of CED 201 over 4000-9000 Å. Figure 2 is a segment of the spectrum over 5000-6000 Å and Fig. 3, over 6000-7000 Å. The abscissae are the wavelength in Angstroms and the ordinates, the relative intensities. In Fig. 2 all the identified luminescence features are indicated. One of the emission features that remains unidentified is indicated in Fig. 3. Some standard emission features are also indicated in these figures. Thus, we were able to discover five individual luminescence emission features in the spectrum of CED 201. As noted above, these observations were made at a Nasmyth focus with a spectrograph that has a rather low dispersion. Some results from our study of this nebula have been described elsewhere [8]. There spectra were obtained at a Coude focus with a spectrograph that has a higher dispersion. There it was possible to identify three emission features as photoluminescence of frozen hydrocarbon particles (4944-5020, 5066-5112, 5175-5314 Å). The positions of the luminescence emission features in these spectra (Coude, Nasmyth) are close. At the same time, there are some differences in the shapes of the luminescence emission features of the spectra obtained at the Coude and Nasmyth foci. It must be emphasized that the two spectrographs had different optical characteristics, including the dispersion.

It is interesting that we have been able to discover luminescence of the dust in CED 201 in the form of individual emission features. This is evidence of the variety of luminescence in interstellar dust. It is now clear that cosmic dust can luminesce in the form of a series of individual, rather narrow emission features, as well as in the form of extended red emission. This was to be expected, since UV radiation in different wavelengths at different temperatures will excite luminescence in frozen hydrocarbon particles (or any other dust particles, including silicon nanoparticles) with different intensities and spectral compositions. It must be acknowledged that there is a lot of dust of various compositions in the galaxy that can luminesce in different regions of the optical spectrum.

5. Conclusion

A model of frozen hydrocarbon particles in the form of a nucleus with a polycrystalline mantle has been proposed in this paper. We have examined the basic properties of these frozen hydrocarbon particles. A comparative analysis allowed us to identify some unknown emission features of the spectrum of the nebula CED 201 as photoluminescence of frozen hydrocarbon particles with a specific chemical composition. Our results show that the dust in reflecting nebulae can luminesce in the form of individual emission features. The correlation of the results obtained at Coude and Nasmyth foci is satisfactory.

In the meantime, it must be pointed out that the emission features that have not yet been identified require further study.

Based on these remarks, we may conclude that studies of the luminescence of nebular dust must be continued using newer methods and instruments.

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REFERENCES

1. I. S. Mathis, W. Rumpl, and K. H. Nordsieck, *Astrophys. J*. **217**, 425 (1977).
2. A. Li and J. M. Creenberg, *Astron. Astrophys*. **323**, 566 (1997).
3. L. S. Spitzer and E. L. Fitzpatrick, *Astrophys. J*. **409**, 299 (1993).
4. J. C. Weingartner and B. T. Draine, *Astrophys. J.* **548**, 296 (2001).
5. B. T. Draine, Electronic publication. Archive: astro-ph/0304489. V. 1. 28 Apr. 15 (2003).
6. W. Duley, *Mon. Not. Roy. Astron. Soc*. **215**, 259 (1985).
7. G. Ledoux, O. Guillois, F. Huisken, et al., *Astron. Astrophys*. **377**, 707 (2001).
8. I. Simonia, *Astrofizika* **47**, 625 (2004).
9. I. Simonia, *Pis'ma v Astron. zh*. **30**, 12, 946 (2004).
10. C. Koike, H. Chihara, K. Koike, et al., MPS **37**, 1591 (2002).
11. K. Koike, M. Nakagawa, C. Koike, M. Okada, and H. Chihara, *Astron. Astrophys*. **390**, 1133 (2002).
12. T. A. Teplitskaya, T. A. Alekseeva, and M. M. Val'dman, Izd-vo. MGU, Moscow (1978).
13. A. N. Witt and U. P. Vijh, ASP Conf. Ser. (2004) (in press).
14. L. B. d'Hendecourt, A. Leger, G. Olofsson, and W. Schmidt, *Astron. Astrophys*. **170**, 91 (1986).
15. W. W. Duley, *Mon. Not. Roy. Astron. Soc*. **258**, 773 (1992).
16. B. S. Gorobets and A. A. Rogozhin, Mineral'noe syr'e 11 (2001).