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LUMINESCENCE OF DUST IN THE NEBULA CED 201

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This article is a study of luminescence in reflection nebulae and other objects consisting of dust or containing solid matter. New concepts and ideas, in particular the concept of frozen hydrocarbon particles, are proposed. Luminescence emission in the spectrum of the reflection nebula CED 201 is studied. Data analysis strategies and the identification process are discussed. Six previously unknown emission features are discovered in the spectrum of CED 201 over 4650-7525 Å. Three are identified as photoluminescence of solid hydrocarbons and the others are ascribed to ERE. It is proposed that the dust component of CED 201 be regarded as a complex of frozen hydrocarbon particles.

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

1. Introduction

Interstellar dust can exhibit luminescence at different intensities in various regions of the spectrum (optical and IR) when irradiated by ultraviolet radiation or charged particle fluxes. Stars of various spectral types and brightnesses serve as sources of radiation that excites this luminescence [1-3]. Dispersed or concentrated in the form of clouds, complexes, or circumstellar disks, dust can have a distinct luminescence under the influence of the exciting radiation [4]. Short wavelength radiation from a star is absorbed by the matter in a dust grain and reradiated in the optical range subject to the persistent condition $E_{abs} > E_{rad}$. The absorbed energy is expended in raising atoms to an excited state. The return of the electrons to their ground state is accompanied by emission of a photon of lower energy (except in the case of radiationless transitions in heated matter). The luminescence carries information on the physical properties of interstellar matter— its chemical and mineralogical composition, crystalline structure, and other characteristics. This information can be obtained through comparative and complementary analysis of astronomical, physical-mineralogical, photochemical, and other data.

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2. Luminescence of solid interstellar matter

The following objects in outer space can have intense luminescence: (1) reflecting nebulae, (2) peculiar objects such as the red rectangle, (3) circumstellar dust disks, (4) dust structures in the solar system, and (5) comets, asteroids, and other small bodies. Micron and nanometer sized dust particles of the following types can also luminesce when irradiated by exciting radiation: (a) carbonaceous dust, (b) siliceous dust, (c) frozen hydrocarbon particles, and (d) dust particles consisting of a pure substance. The concept of dust particles in the form of frozen hydrocarbon particles is introduced below. We believe that the luminescence of nanometer sized dust particles carries information about the "structural material" of stars. The luminescence of dust grains (micron-sized particles), on the other hand, carries information about the evolution of matter during the formation of planetary systems.

Laboratory experiments show that frozen O and N demonstrates intense luminescence when irradiated by ultraviolet radiation and cathode rays [5]. We assume that similar effects can take place in outer space, when dust particles with a mantle of oxygen or nitrogen with temperatures of 50-65 K show up in the field of action of hard radiation. Reflecting nebulae are among the class of objects in outer space whose dust luminesces intensely under irradiation. Ultraviolet radiation from the illuminating stars excites luminescence in the dust grains of nebulae, and simultaneously photoprocesses their surfaces. In some cases, fluxes of IR radiation can quench the luminescence of dust grains or intensify it. Variable or constant fluxes of charged particles (electrons) can also intensify the luminescence of dust particles in nebulae. It should also be noted that the absorption of radiation by dust particles causes changes in their luminescence properties. The luminescence spectrum of reflecting nebulae is determined by (1) the chemical-mineralogical composition of the dust, (2) the temperature of the dust, (3) the characteristics of the crystalline lattice of the dust grains, (4) the formation time and stage of evolution of the matter in the dust, (5) the spectral type of the illuminating star, (6) the brightness of the illuminating star, (7) various features of the "star-dust" system, and (8) the spatial configuration of the "star-dust-observer" system. Here we only provide a brief description of the most important aspects of the luminescence process for solid interstellar matter. A detailed discussion of this process will be given in a separate article.

3. Preparation of the observational experiment

Having examined a number of important aspects involved in the study of the luminescence of solid matter in outer space, we now turn to the practical side of the question. In choosing reflecting nebulae as objects in an "astrophysical laboratory" [6] the came upon the task of preparing and carrying out an observational experiment in practice. Our basic instrument was the 2 meter telescope at the TLS Observatory (Germany). Having Coude and Naismith foci in combination with high resolution spectrographs, it seemed to us to be an extremely suitable instrument. (Our hopes were justified.) Given the optical properties of the instrument and the astroclimate of the TLS Observatory, our basic strategy was to obtain a spectrum of the nebula and a spectrum of the illuminating star, and then to divide them. The most difficult part was choosing a suitable object. Clearly, this choice could be made subject to the technical capabilities of the instruments. We settled on the reflecting nebula CED 201 (vdB 152). The illuminating star is BD+69°1231, which is of spectral type B9.5V. CED 201 has been well studied. We were extremely interested in the unusual properties of this nebula: dust albedo, excess reddening, strong UV absorption at 2175 Å, and the possible absence of a "genetic" relationship between the illuminating star and the nebula [7,8]. *BVI* photometry of CED 201 has been described by Witt and Schild [1]. They showed, in particular, that CED 201 is substantially redder in the *V* and *I* regions than might be expected if the brightness of this object is examined only in terms of conventional scattering by dust particles. They believe that this indicates that CED 201 has extended emission in the *I* band. They treat the extended I-band emission as photoluminescence of the nebular dust excited by UV radiation from the illuminating star. They propose a range of $1800 < \lambda < 2500$E for the UV excitation source. A number of objects with extended red emission have been examined elsewhere [3]. These objects include, in particular, NGC 7023, NGC 2023, and CED 201. These authors consider the extended red emission to be an indicator of the presence of carbonaceous dust particles in the nebular dust. The general properties of this extended red emission have been summarized in Ref. 9. In particular, it is shown there that this emission is observed in many astrophysical dust objects and consists of a structureless band over the range 5400-9400 Å. The extended red emission is regarded as the photoluminescence of dust particles. The candidate sources of the extended red emission include nanometer sized carbonaceous dust and siliceous dust, and several other dusty substances. The discussion on the nature of extended red emission continues. We would like to point out that a number of special conditions have to be met in order to observe this emission, specifically, observations must be made under highly transparent atmospheric conditions and over a wide spectral range using low dispersion spectrographs.

4. Observations and data processing

Spectra of the reflecting nebula CED 201 were obtained using the 2 meter reflector and the Coude-echelle spectrograph at the TLS observatory (Tautenburg). The diffraction grating of the spectrograph had 600 lines/mm. In order to improve the signal to noise ratio, only the first order of the grating was used; by reducing the spectral resolution we increased the signal yield by a factor of 10. The slit of the spectrograph had a width of 2.9 arc seconds and a length of 29 arc seconds.

Initial processing of the spectra was by standard program packages to, in particular, the following: filtering the cosmic background, flat field compensation, extracting the spectrum, and wavelength calibration with a ThAr lamp. The exposure time was 30 min. Spectra of CED 201 were obtained in the range 4650-7525 Å. Given the faintness of the luminescence signal and the three-dimensional geometric features of CED 201, a special strategy was employed for processing the spectrum. The essence of this strategy is to represent the spectra in the form

$$N = n + b \tag{1}$$

$$S = s + n + b, \tag{2}$$

where *N* is the peripheral region of the nebula, *S* is the region of the star, *n* is the intrinsic contribution from the nebula, *s* is the intrinsic contribution from the star as modified by the nebula, and *b* is the contribution from the night sky. Spectra were obtained of region *S* with the illuminating star at the center of the slit and of region *N* (the periphery of the nebula away from the star). The separation between *S* and N was 14 arc seconds. Ignoring the negligible magnitude of the modification in the intrinsic contribution from the star by the nebula, this yielded

$$r = (N - b)/(S - N). \tag{3}$$

Equation (3) is a numerical reflection of the strategy for processing the spectrum of the nebula. *b* was obtained separately, outside the nebula, with the same exposure time. (The corresponding regions of the resulting spectrum, *r*, are shown below.) This strategy made it possible to detect the luminescence of the dust in the nebula CED 201 in the form of individual emission bands with extremely well defined positions and shapes. We should add that standard methods were used for normalization to the local continuum.

5. Results

The spectrum is shown in Figs. 1, 2, and 3, cut up into segments that show the corresponding fragments of the resultant spectrum of the nebula and of the derived continuum above which the luminescence emission stands. (The axes correspond to the wavelength λ in Å and the relative intensity *I*, respectively.) A few standard emission bands are also indicated in these figures. This spectrum was compared with the spectra of known sources of radiation of terrestrial and cosmic origin. In particular, it was compared with a set of forbidden lines, emission from planetary nebulae, and artificial emission sources including mercury (Hg) and sodium (Na), as well as with emission from other sources. The coincidence of the positions of the bands in our spectra with those in the spectra of the known radiation sources made it possible to assign some of our bands to known radiation sources and thereby eliminate them from the search procedure for luminescence emission sources. After detailed comparisons and the elimination of all the known emission sources, several emission bands of unknown nature remained in our spectrum: 4944-5020, 5066-5112, 5175-5314, 6106-6121, 6640-6654, and 7497-7509 Å. We also observed an emission line at l=6804 Å. It has been shown [10] that l=6803.08 Å is a satellite line of the hydroxyl OH radical in the spectrum of the night sky. This made it possible to eliminate our emission at 6804 Å from the list of unknown emissions. We propose that the unknown emission we have observed in the spectrum of CED 201 be regarded as photoluminescence of the nebular dust.

We decided to compare the identified unknown emission bands with the luminescence of the 300 most widespread minerals described in Ref. 11. This comparative analysis yielded 18 candidate minerals corresponding to the following criteria introduced in Ref. 12: (1) simplicity of the mineral composition, (2) exact coincidence of the luminescence emission bands of the mineral with unknown emission bands in the spectrum of CED 201, and (3) widespread distribution within the universe of the chemical elements making up a mineral. As to point 3, it should be noted that during selection preference was given to more widely distributed elements. After an attentive analysis of the spectral locations, and of the closeness or similarity of the corresponding profiles, we obtained the following final results: (1) 4944-5020 Å, diamond C; (2) 5066-5112 Å, diamond; (3) 5175-5314 Å, diamond; and, (4) 7497-7509, periclase, MgO. The emission bands at 6106-6121 Å and 6640-6654 Å remained unidentified within the confines of this procedure. It should be noted that the luminescence emission profiles of diamond (C) and periclase (MgO) do not coincide exactly with those of the unknown emission bands in the spectrum of CED 201. Thus, the probability that grains of diamond and periclase might form part of the dust in CED 201 and be the sources of the unknown emission bands, is very low.

We have, therefore, carried out another comparative analysis drawing on laboratory data on chemical compounds of a different kind. In particular, we made a comparison with a set of luminescence spectra of polycyclic aromatic hydrocarbon molecules. The abundances of these compounds in outer space are known [9]. We compared our emission bands with the luminescence spectra of polycrystalline aromatic hydrocarbons in the form of a polycrystalline solution

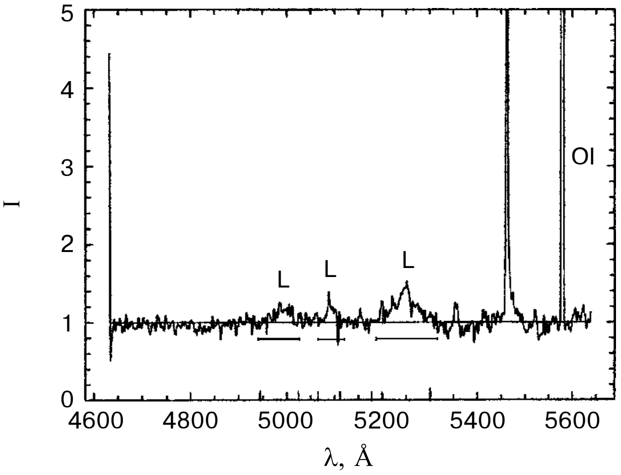

Fig. 1. The resultant spectrum of CED 201, 4600-5600 Å. The letters correspond to the identified luminescence emission of frozen hydrocarbon particles.

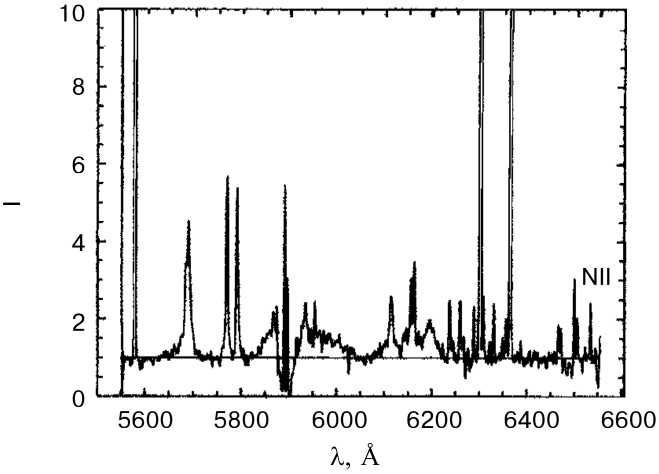

Fig. 2. The resultant spectrum of CED 201, 5600-6600 Å.

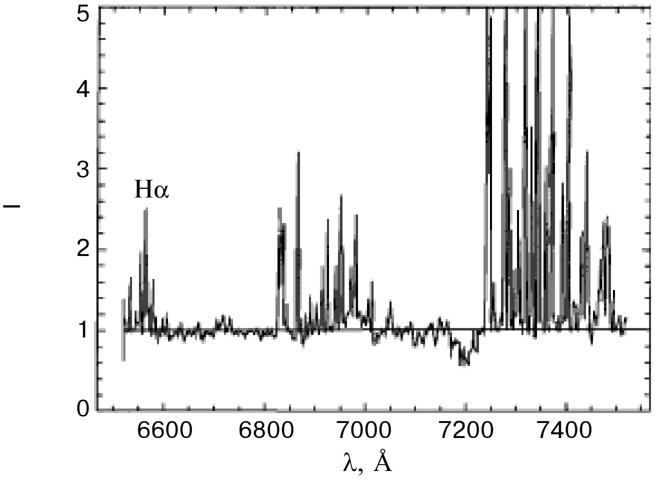

Fig. 3. The resultant spectrum of CED 201, 6600-7525 Å.

with acyclic hydrocarbons (with hexane or heptane) at a temperature of 77 K. Data from Ref. 13 were used for comparison. The analysis showed that in the solid solution form (77 K), 2,3-orthophenylenepyrene $C_{22}H_{12}$ has fluorescence emission bands at wavelengths of 4955, 4970, and 5005 Å. With increasing temperature, the fluorescence bands of this hydrocarbon broaden. The fluorescence emission bands of $C_{22}H_{12}$ lie within the limits of our first band, 4944-5020 Å. We propose treating this compound as a source of luminescence emission bands in the spectrum of CED 201. 2,3-orthophenylenepyrene also fluoresces at 5106 Å. This emission band lies within the limits of our band at 5066-5112 Å, although this emission at 5106 Å is quite weak under laboratory conditions. It should also be noted that other polycrystalline solutions luminesce within this band. For example, at 77 K a solid solution of tetracene $C_{18}H_{12}$ has fluorescence at 5073, 5083, and 5087 Å. Phenanthrene $C_{14}H_{10}$ in the form of a solid solution (77 K) has phosphorescence at 5313 Å. This emission lies within our band at 5175-5314 Å. The width of the phosphorescence band of phenanthrene will also increase with rising temperature. Thus, phenanthrene and other hydrocarbons in the form of a frozen mixture with acyclic hydrocarbons can be the source of the luminescence in CED 201. We propose that the dust particles in CED 201 are frozen microscopic grains made up of a mixture of polycyclic aromatic hydrocarbons with acyclic hydrocarbons. The comparative analysis with the luminescence emission bands of solid hydrocarbon solutions did not yield identifications for the following unknown emission bands in the spectrum of CED 201: 6106-6121, 6640-6654, and 7497-7509 Å. We believe that these three bands may be components of the extended red emission customarily detected in reflecting nebulae using low dispersion spectrographs [14].

We believe that the dusty material in the nebula CED 201 consists of frozen microscopic particles with a complicated chemical composition of which the major components are polycyclic aromatic hydrocarbons and acyclic hydrocarbons. These frozen particles may consist of a core and a polycyclic mantle. A particle consisting of a finely dispersed carbonaceous core covered with a polycrystalline mantle made up of a mixture of aromatic and acyclic hydrocarbons will be characterized by its mass, size, albedo, etc. Irradiated by UV radiation from an illuminating star, the frozen particles of dust matter in a nebula will luminesce in the corresponding region of the visible spectrum. We propose calling this kind of particle “frozen hydrocarbon particles.”

Laboratory data [13] show that the bands in the luminescence spectrum of frozen hydrocarbon particles will be broadened as the temperature of the material increases or as the concentration of the aromatic or acyclic components in the mixture decreases, as well as in a variety of other cases. This broadening can be significant and in extreme cases of a significant temperature rise, a fairly narrow band can be transformed into a broad, diffuse band. Given the diverse chemical composition of the hydrocarbons in the aromatic series, we may conclude that under different physical conditions in different reflecting nebulae frozen hydrocarbon particles will have different luminescence spectra. It has also been shown [13] that the luminescence quantum yield of these mixtures is very high at low temperatures. The luminescence quantum yield of frozen hydrocarbon particles will also be extremely high, which, in turn, determines the relative ease of detecting the luminescence signal from these dust objects.

We have detected the luminescence emissions in several spectrum of the reflecting nebula CED 201 for the first time in our observational experiment. Only an extended red emission has been observed previously, and this has been regarded as photoluminescence of the nebular dust [14]. Ideas regarding the chemical composition of the dust in reflecting nebulae are still in the formation stage. Thus, it has been stated [15] that the dust in reflecting nebulae consists of carbonaceous grains enriched in hydrogen and shown [14] that the material in reflecting nebulae consists of nanometer-sized siliceous dust particles. There are other opinions, as well. The discussion on this topic continues.

Here we have proposed the concept of frozen hydrocarbon particles in the form of a carbonaceous core surrounded by a polycrystalline mantle for the first time. This outer shell consists of a mixture of frozen aromatic and acyclic hydrocarbons. We believe that this kind of particle may be encountered in various gas-dust objects in the galaxy, as well as in bodies in the solar system that are rich in dust. The observations have been made in rather complicated astroclimatic conditions. We have used all the technological capabilities of the TLS Observatory in order to detect the faint luminescence signal from the dust in the nebula CED 201.

6. Conclusion

In September-December 2001 we conducted a study of the nebula CED 201. Spectra of this nebula were taken using the 2 meter telescope and echelle spectrograph of the TLS Observatory. By processing the data in a special way, we have been able to detect the luminescence emission of the dust in this reflecting nebula. A comparative analysis shows that the dust in CED 201 consists of a mixture of frozen aromatic and acyclic hydrocarbons. We have proposed the concept of frozen hydrocarbon particles. The comparative analysis was difficult because of the somewhat disordered and disparate nature of the available laboratory data.

Several important aspects of the luminescence of dust in outer space have been discussed and several new ideas have been proposed in this paper. We are coming out with an initiative to prepare a special atlas of luminescence emission from reflecting nebulae. Such an atlas might contain basic data from studies of the luminescence of reflecting nebulae, two dimensional spectral scans, and much else. A summary atlas of this kind could draw on data obtained from different observatories all over the world and with different instrumentation.

We hope that this paper will extend the range of current ideas on the luminescence of dust in reflecting nebulae and stimulate further research in this interesting area.

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