Astronomical and Astrophysical Transactions (*AApTr*), 2020, Vol. 31, Issue 4, pp. 431–442,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Formation and evolution of dust grains in the hard radiation field: astrophysical applications

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Received 1 October, 2019

This paper discusses the effects of hard radiation and cosmic rays (hereafter "CR") on the state and evolution of the gas-and-dust component of AGN. One of the causes of the current diffuse and scattered X-ray emission excesses from the sub-30 nm dust grains in the vicinity of compact relativistic sources is shown. We have continued a series of studies initiated by other researchers on the processes of photoemission from the surface of dust grains and generation of the surface potential φ, as well as their impact on the condensation and further evolution of dust grains. Additional channels for the nebular plasma heating by Auger electrons are specified. In particular, it is shown that it is Auger electrons that are responsible for the rise in the temperature of particles forming gas-and-dust aggregates rather than induced optical emission. It has been deduced that scattered and induced diffuse soft X-ray emission is determined by the penetrating power of strong hard radiation and CR. As a result, deeper layers of the galactic disc comprising AGN become "visible" in the optical and IR spectral regions. It has been observed that the dust exposure to hard radiation results not only in micro dimensions of dust grains, but also in the absence of any amorphous shell.

Keywords: Active galactic nuclei, interstellar dust, cosmic rays

1 Introduction

This paper completes a series of studies on the properties of the dust component in the vicinity of active galactic nuclei (AGN), young supernova remnants (SNR) and other sources of CR and high-energy quanta. The radiation field structure determined on the basis of space observations carried out with the Compton Gamma Ray Observatory (CGRO), INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) and Fermi Gamma-ray Space Telescope enabled us to add to the ground-based observations of some of the target objects and subsequently compile extensive catalogues of galaxies hosting AGN, in particular in the γ (1 GeV), X-ray (1 keV), optical and radio bands.

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The interaction between radiation fluxes with the above-specified energies and interstellar dust allowed us to obtain totally new data which are essential for diagnostics of dusty media in the hard radiation field. In the previous paper (Doikov, 2019a), the author discussed the study of electrophysical properties of the dispersed dust component during its formation associated with the exposure to such radiation and also reported the total relationships for its key parameters, such as size distribution, surface potential and distinctive structural features. The chemical composition of interstellar dust grains was thoroughly examined in the IR portion of the spectra of the same objects (Dwek, 1987), (Dwek et al., 2008).

In particular, we obtained the ratios between the contents of astronomical silicates (containing such elements as Si, Mg, Fe and O), carbon-bearing particles in the form of graphite and other dust components containing carbon, oxygen and less commonly nitrogen. Despite a variety of sources of dust formation in the galaxies that have already passed through the AGN phase, in the galaxies hosting AGN dust grains are formed either in the nebular aggregates or young supernova remnants. The dust composition in the gas-and-dust aggregates is determined by the chemical composition of the gas. In the supernova remnants and planetary nebulae, the dust may be a mixture of the circumstellar and interstellar constituents, and that complicates the interpretation of its origin. Using observational data obtained practically in all spectral bands makes it possible to determine and distinguish between contributions of all dust components. Interpreting observations carried out with the Spitzer Space Telescope enabled us to determine such thermodynamic properties of dust as temperature and average molar mass. The dust has been examined by its black-body radiation including characteristic far-IR emission components. It is these characteristic emission bands that allowed us to separate silicates from hydrocarbons. Being in the proximity of the relativistic active objects, such as galaxies hosting AGN, the dust is exposed to hard radiation. Similar conditions are typical for young supernova remnants. In this case, photoemission occurs with simultaneous acquisition of the surface potential by the particles and their nuclei. Such a phenomenon when the hard-radiation-induced flux of electrons from the surface of dust grains is not compensated by the reverse electron flux leads to the so-called photoemission. The electron energy distribution function $F(E)$ will have two peaks in such media – namely, a Maxwellian (thermal) peak and the Auger (high-energy) peak. AGN are predominantly embedded in the local magnetic field with the strength reaching hundreds of gauss, thus gas-and-dust aggregates will produce specific two-component synchrotron radiation. Relativistic electrons in the galactic centre are responsible for the first radiation component while the Auger electrons or recoil electrons with lower energies emit the second one. The key ratios describing the formation and evolution of the condensed phase were reported in the previous paper of the author (Doikov, 2019a). In this study, we will employ those ratios at the luminosities adopted from catalogues at the energies of 1 GeV for γ-rays and 1 keV for X-rays with application of optical band-pass filter. Similar to the studies (Doikov, 2019a), (Hasegawa and Kozasa, 1988), when calculating the formation of the condensed phase, we set the luminosities at the given energies to the following values: $\log(L_\gamma(1\text{ GeV})) = 43$; $\log(L_X(1\text{ keV})) = 43$; and $\log(L_0) = 43$.

Here the values are expressed in erg/s units. As shown in (Doikov and Yshchenko, 2019c), it would be more accurate to consider the first two fluxes as initial ones and the third flux as an induced one. We will use the given luminosities in the vicinity of

the AGN centre while in the periphery we will employ the induced X-ray flux which is weaker by a factor of 2. Meanwhile, the γ- and X-ray emission along the galactic disc is almost totally absorbed at the distances of tens of parsecs due to the presence of dust grains. As the optical and IR luminosity of AGN is extremely bright, the author has considered some alternative sources of excitation. This paper consists of three sections, each of which solves the problem of specifying distinctive physical features of the dispersed phase formation and its reverse effects on the hard radiation field. In the conclusion, the findings are analysed and new problems are set as targets for the further laboratory experiments and space observations.

2 Formation of particles in the field of γ-(1 GeV) quanta

Observations of γ-quanta (1 GeV) and X-ray emission (1 keV) of the galaxies hosting AGN with specific features are available in numerous extensive catalogues and make it possible to separate uniform series of galaxies. Such objects include BL Lacertae galaxies with reduced flux of matter due to the presence of massive black holes.

Jets formed under such conditions produce luminosity at the given energies. Hard radiation and particles penetrate the remaining part of AGN. However, the environment changes in cold gas-and-dust aggregates in AGN wherein condensation occurs under normal conditions. Anyway, creating conditions for the formation of condensation nuclei requires a certain degree of super-saturation in the localised region of the galactic disc. In the absence of hard radiation, super-saturation sufficient for the condensation is commonly observed in gas-and-dust aggregates as the equilibrium temperature of the gas is far lower than the temperature of the saturation vapours ascribed to relevant monomers at the current concentrations and temperatures of the gas. Thus, the flux of atoms and molecules through the surface of the condensation nucleus is not compensated by the reverse flux of those particles. The formation of seed condensation nuclei is called nucleation and can be described with the following relationship (Hasegawa and Kozasa, (1988), formula 2; Doikov (2019a)):

$$J_j^s(t) = \alpha_{S_j}\Omega_j\left(\frac{2\sigma_i}{\pi m_{1j}}\right)^{1/2}\cdot\left(\frac{T}{T_d}\right)^{1/2}\Pi_j l_{1j}\exp\left[-\frac{4}{27}\frac{\mu_j^2}{(\ln S_j)^2}\right]. \quad (1)$$

Here α_{S_j} is the probability of the k^{th} cluster adhesion to a particle (it is set to $\alpha_{S_j} = 1$ in (Hasegawa and Kozasa, 1988), which is not the case in this study); Ω_j is the volume of the condensed monomer; σ_i is the monomer surface energy; Π_j is the function of the gas partial pressure $\Pi_j = 1$; μ_j is the dimensionless energy barrier for nucleation calculated by the following formula: $\mu_j = \frac{4\pi\alpha_{0j}^2\sigma_j}{kT_d}$, where k is the Boltzmann constant, $\alpha_{0j} = \left(\frac{3\Omega_j}{4\pi}\right)^{1/3}$ is the average molar size. The degree of supersaturation S_j for the condensation reactions is defined by the following relationship: $\ln(S_j) = -\frac{\Delta G_J^0}{kT_d} + \Sigma_i\nu_{ij}\ln P_{ij}$, where P_{ij} is the partial pressure

of gas; ν_{ij} is a symbol denoting reactants as "+" and their products as "–"; T_d is the intrinsic temperature of the condensed dispersed phase particles; S_j is the degree of supersaturation of a j-type monomer.

The following equations, which are reckoned to be more convenient with regard to the interpretation of the experimental findings (Kozma et al., 1992), are frequently used to describe the growth of carbonate grains:

$$\frac{da_j}{dt} = \alpha_{Sj}\Omega_j\left(\frac{kT}{2\pi m_{1j}}\right)^{1/2}C_{1j}(t) \tag{2}$$

or

$$\frac{da_j}{dt} = \alpha_{Sj}\left(\frac{4}{3}\pi\alpha_{i,0}^3\right)\sqrt{\frac{kT_{gas}}{2\pi m_i}}C_{1j}(t)\left(1-\frac{1}{S_i}\sqrt{\frac{T_d}{T_{gas}}}\right). \tag{3}$$

Here $C_{1j}(t)$ is the current concentration of monomers of a given type. Under such conditions, the collision rate ν is defined by the following formula: $\nu = \sigma C_{1j}(t)V$ where V is the thermal velocity of monomers; σ is the cross-section for their collisions which equals to the geometrical cross-section $\sigma = \pi\alpha_J^2$. Finally, in the interstellar medium without hard radiation the size distribution of dust grains can be written as follows $N(a) = N_0 a^{-3.5}$. This distribution pattern $N(a)$ has been substantiated by numerous observations of the interstellar medium and its constituent gas-and-dust aggregates. The appearance of rather strong fluxes of γ- and X-ray quanta in the examined aggregates has the following effects. Atoms and molecules constituting dust grains undergo energy losses due to ionising radiation of γ- and X-ray quanta. In particular, γ-quanta undergo inelastic collisions with the K-shell electrons which result in the atomic photoeffect with the cross-section σ_K.

The cross-section for this process at the given energies is three orders of magnitude smaller than the cross-section for Compton scattering σ_c: ($\sigma_K/\sigma_c \approx 10^{-3}$, $\sigma_c \approx 10^{-3}\sigma_T, \sigma_T = 6.65\cdot 10^{-25}\,\mathrm{cm}^{-25}$). The production of electron–positron pairs at the given energies is neglected (Gould, 1975, Fig. 1).

The laboratory irradiation of astronomical silicates and several types of carbonates (carbon-containing modifications) using different types of radiations has shown that in terms of the dust grain density in the galactic discs the Compton scattering events quench γ-quanta of the given energies at a distance about tens of parsecs from the centre of AGN and even hundreds of parsecs when creating K-vacancies. If we take into account the density of matter which increases towards the centre of galaxies hosting AGN, then the above-specified scales should be revised downwards. These representations provide the upper estimate of γ-radiation. Lower frequency (and consequently, lower energy) of γ-quanta results in greater cross-sections σ_K and σ_c with the ratio between them σ_K/σ_c being revised downwards as the difference between the cross-sections, as well as the scales of their complete absorption, decrease. The afore-described processes allow us to understand their effect on the evolution of the dust component. It implies that incoherent scattering of γ-quanta and creation of K-vacancies in dust grains is induced by every single chemical element comprising

these dust grains. The production of high-energy electrons as a result of the mentioned types of scattering makes the photoemission of electrons from the surface of these particles possible. Such events are essential when the energy loss due to ionization is very likely in the near-surface layer of particles with a depth not exceeding 10 nm (Doikov, 2019a), (Weingarter and Draine, 2001), (Weingarter et al, 2006) luminosity of AGN in the energy range of γ-rays reaches (10^{45}–10^{46}) erg/s; thus, we can expect quite high values for the fluxes J_γ and J_x, and hence, significant rates of ionisation. Therefore, in order to determine the total energy loss in such dusty media, when calculating the energy loss due to ionising interaction between γ- and X-rays with dust grains, it is necessary to estimate the coefficient for the conversion of the photon energy into radiation. Taking into consideration both mechanisms of energy loss due to ionisation (namely, Compton scattering and atomic photoeffect), we should note that the highest coefficient for the transfer of the photon energy to the surrounding medium corresponds to Compton scattering (Gould, 1975). One of the causes of such heating is the creation of the near-surface layer of particles by the Auger electrons. This effect in gaseous medium has been studied in (Kozma and Fransson, 1992), (Doikov et al., 2018). In this case, the degree of supersaturation decreases, then with increasing temperature the evaporation of dust particles is initiated. Ionisation of atoms forming dust grains due to the interaction with soft γ-rays is of interest with regard to the spectroscopic studies of the peripheral regions of AGN. The gas component is represented by a greater mass fraction of the relevant atoms of the CNO group, as well as Si, Mg and Fe. Based on the study (Kozma and Fransson, 1992, p. 604, formula (13) and Table 2A), we consider the ionisation rate $\Gamma_i n_i$ per unit volume for the afore-listed elements. The formula given below is also justified for the calculation of ionisation of atoms comprising solid interstellar particles:

$$\chi_{eff,i}(x_e) \;=\; \frac{I_i X_i}{\eta_{ik}(x_e)}, \Gamma_i n_i \;=\; \frac{4\pi J_\gamma \sigma_{\gamma,i}}{\chi_{eff,i}(x_e)} \tag{4}$$

where J_γ is the mean strength γ-emission; $\sigma_{\gamma,i}$ is the energy-mean cross-section of an ion of i-type as a function of its density and γ-ray source energy distribution. The absorption coefficient κ_γ and cross-section $\sigma_{\gamma,i}$ in the indicated studies are defined by the following equations:

$$\kappa_\gamma \;=\; 0.06\left(\frac{Z_i}{A_i}\right)\mathrm{cm}^2\mathrm{g}^{-1},\; \sigma_{\gamma,i} \;=\; 0.06 Z_i m_p \mathrm{cm}^2 \tag{5}$$

Here Z_i is the ionic charge and A_i is its atomic mass. For the target elements $\frac{Z_i}{A_i} \;=\; 0.5$. We can adopt initial data required for the further calculations, as well as for the determination of the earlier mentioned effective potential-$\chi_{eff,i}(x_e)$ from Table 2A (p. 607, Kozma and Fransson, 1992)).

$$\chi_{eff,i}(x_e) \;=\; C \cdot 10^{\alpha}\;,\; \alpha \;=\; \Sigma_{i=1}^{4} a_i (\log_{10}(x_e) \;+\; 4)^i. \tag{6}$$

Table 1 Semi-empirical parameters required for the calculation of the effective potential $\chi_{eff,i}(x_e)$ and rate of ionisation of matter exposed to γ-quanta flux J_γ for individual elements comprising dust grains.

Element	C (eV)	a_1	a_2	a_3	a_4	$\chi_{eff,i}(x_e)$	$\Gamma_i n_i$
C I	8.50	$-0.1294 \cdot 10^{-01}$	$0.3135 \cdot 10^{-01}$	$-0.1878 \cdot 10^{-01}$	$0.6176 \cdot 10^{-02}$	8.935	$8.22 \cdot 10^{-11}$
C II	36.64	$-0.3969 \cdot 10^{-02}$	$0.1833 \cdot 10^{-01}$	$-0.1636 \cdot 10^{-01}$	$0.6137 \cdot 10^{-02}$	35.552	$2.07 \cdot 10^{-11}$
N I	10.57	$-0.1215 \cdot 10^{-01}$	$0.2990 \cdot 10^{-01}$	$-0.2033 \cdot 10^{-01}$	$0.6551 \cdot 10^{-02}$	10.342	$8.28 \cdot 10^{-11}$
N II	35.40	$-0.1136 \cdot 10^{-01}$	$0.3089 \cdot 10^{-01}$	$-0.2398 \cdot 10^{-01}$	$0.7231 \cdot 10^{-02}$	32.600	$2.63 \cdot 10^{-11}$
O I	10.59	$-0.1167 \cdot 10^{-01}$	$0.3196 \cdot 10^{-01}$	$-0.2269 \cdot 10^{-01}$	$0.6902 \cdot 10^{-02}$	10.756	$9.10 \cdot 10^{-11}$
O II	33.88	$-0.1315 \cdot 10^{-01}$	$0.3242 \cdot 10^{-01}$	$-0.2551 \cdot 10^{-01}$	$0.7473 \cdot 10^{-02}$	30.834	$3.18 \cdot 10^{-11}$
Mg I	3.18	$0.2266 \cdot 10^{+00}$	$-0.3135 \cdot 10^{-01}$	$0.4768 \cdot 10^{-02}$	$0.7473 \cdot 10^{-02}$	8.311	$1.77 \cdot 10^{-11}$
Mg II	29.11	$-0.1766 \cdot 10^{-01}$	$0.3944 \cdot 10^{-01}$	$-0.2315 \cdot 10^{-01}$	$0.6644 \cdot 10^{-02}$	26.513	$5.54 \cdot 10^{-10}$
Si I	3.17	$0.2028 \cdot 10^{+00}$	$-0.3949 \cdot 10^{-01}$	$0.5850 \cdot 10^{-02}$	$0.2772 \cdot 10^{-02}$	6.801	$2.52 \cdot 10^{-11}$
Si II	19.67	$-0.5790 \cdot 10^{-02}$	$0.1466 \cdot 10^{-01}$	$-0.8207 \cdot 10^{-02}$	$0.4630 \cdot 10^{-02}$	51.578	$3.32 \cdot 10^{-11}$
Fe I	8.44	$0.1011 \cdot 10^{+00}$	$0.2084 \cdot 10^{-01}$	$-.1181 \cdot 10^{-01}$	$0.4609 \cdot 10^{-02}$	14.638	$2.17 \cdot 10^{-11}$
Fe II	15.52	$-0.1316 \cdot 10^{-01}$	$0.2725 \cdot 10^{-01}$	$-0.1729 \cdot 10^{-01}$	$0.6007 \cdot 10^{-02}$	13.657	$2.33 \cdot 10^{-10}$

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3 Formation of particles in the radiation field with the energy of 1 keV

The pattern of the X-ray luminosity of BL Lac type AGN at the energy of 1 keV is similar to that of the γ-band luminosity. Unlike the fluxes emitted at the energy of 1 GeV predominantly from the very centre of AGN, soft X-rays can be emitted as primary radiation (associated with the centre of AGN) and induced radiation all around AGN. At the luminosities adopted from catalogues, the radiation field density is sufficient for the ionisation of matter and further excitation of optical transitions. In particular, light (Li, Be and B) and CNO elements undergo atomic photoeffect and ionisation at higher energy levels. We managed to trace the relationship between variable X-ray fluxes and dust temperature in young supernova remnants (Dwek, 1987), (Dwek et al., 2008). In AGN, such a relationship can be inferred taking into account the spectra of target hard radiation. If the carbon-bearing dust grains are irradiated with soft X-rays (at 1 keV), then the generation of the surface charge on a grain and consequently the surface potential change the nucleation process fundamentally if exposed to hard radiation (Doikov, 2019a). This issue is described in detail in the previous paper of the author. In this paper, we only report the results related to the problem in question. The rate of ionisation by creating K–L-shell vacancies in CNO elements can be described to a first approximation by formulae (4)–(6). The emitted Auger electrons carry kinetic energy sufficient to reach the surface of the dust grain and leave it. In so doing, the dust grain acquires a positive charge. The soft X-ray and hard UV radiation are more effective in ionisation of almost every single atom and molecule.

Let us consider the condensation of dust grains and their further evolution under such conditions. To this end, we should determine the generation of the surface potential of a particle and its effect on the particle's growth rate. In this case, we can write the following formula:

$$\frac{da}{dt} = \alpha_{Sj} \exp\left(-\frac{e\varphi}{\kappa T}\right)\left(\frac{4}{3}\pi a_{i,0}^3\right)\sqrt{\frac{kT_{gas}}{2\pi m_i}}C_{1j}(t)\left(1-\frac{1}{S_i}\sqrt{\frac{T_d}{T_{gas}}}\right). \tag{7}$$

The first two factors show decreasing coefficient of adhesion due to the surface potential of a particle φ. The collisional cross-section σ as a function of the surface potential φ and charge q can be written as follows:

$$\sigma = \pi\alpha^2 \begin{cases} 1-\frac{q\varphi}{E_i}, & E_i > q\varphi \\ 0, & E_i \leq q\varphi \end{cases}. \tag{8}$$

Having acquired the total charge Z, the condensation nucleus changes the pattern of the particle adhesion $S_i(Z)$. The adhesion coefficient $S_i(Z)$ for hydrocarbonate-containing grains can be written as follows:

$$S_i(Z) = \frac{\langle\sigma\nu\rangle}{\left(\frac{SkT}{\pi m_i}\right)^{\frac{1}{2}}\pi\alpha^2\vec{J}(\tau,\nu)}. \tag{9}$$

Note that the growth rate of dust grains upon adhesion of monomers to their surface is very sensitive to $S_i(Z)$. By substituting $S_i(Z)$ from equation (9) into the formula for the growth rate of dust grains in the presence of the accretive flux of monomers onto the surface of accreting seed grain we will obtain the following relationship:

$$\frac{da_i}{dt} = \frac{\langle \sigma\nu \rangle}{4\pi\alpha^2 \vec{J}(\tau_i, \xi_i)} \Omega_i n_i(t), \tag{10}$$

$$\vec{J}(\tau, \nu) = \int_0^\infty x e^{-x} \tilde{\sigma}(\varepsilon = x(\tau, \nu)) dx. \tag{11}$$

Table 1 presents the data factoring in the correlation between the rate of ionisation of atoms comprising dust grains, which is expressed by formulae (4)–(6), and the hard radiation field density $\vec{J}(\tau, \nu)$. The establishment of the apparent correlation between the coefficient for the sticking of monomers to a particle and its surface potential φ in this study enables us to conclude that hard CR (namely, γ- and X-rays) induce generation of the surface potential. In this case, the absorption (adhesion) of positively charged monomers in the form of atoms and molecules to the dust grain surface is terminated under conditions of the AGN interstellar medium and young supernova remnants. The only exception applies to the atoms and molecules with high kinetic energies $E_i > q\varphi$ in equation (8). Due to the limited rate of nucleation and growth of dust grains in young supernova remnants, the formation, nucleation and growth of particles occur over a very short time interval which is much shorter than the time of the gas relaxation to equilibrium. However, within a given period of time the growth rate of particles decreases, and then it is prevented under conditions specified in formula (8). Hard radiation upregulates the temperature of dust grains and promotes photoemission from their surface that increases the likelihood of the evaporation of atoms. The presence of the surface potential results in decreasing surface tension coefficient and also facilitates the evaporation of loosely bound atoms of the amorphous shell of dust grains. Observations of the X-ray halos around compact relativistic objects have confirmed the overwhelming prevalence of sub-30 nm dust grains.

4 Spectroscopic features of the presence of dust grains in the hard radiation field

From the results of the previous section, we can deduce that due to the total effect of the hard radiation field on the condensed phase of the interstellar medium the large end of the size distribution of dust grains $N(a)$ is tailed off more markedly. It means that almost all the dust grains fall into the range of 1–30 nm. The wavelength of an X-ray quantum with the energy of 1 keV is $\lambda_X = \dfrac{hc}{E_X} \approx 1.2$ nm. Optical characteristics of quartz and carbon-bearing dust were specified in (Doikov et al., 2018, 2019c). Anomalous diffraction can be observed for sub-30 nm dust grains.

Unlike other types of scattering, anomalous X-ray diffraction is the most effective for the particles of 1–20 nm in size. To make it clear, we will make pre-estimates given that the density per cubic parsec of AGN is $400M_{\odot}$. If we consider a cylinder-shape area in the vicinity of AGN with the base of 1 pc and height of 200 pc, then the quantity of 10 nm dust grains of a certain type in this area makes 10^{56}. The quantity of generated X-ray quanta at the AGN luminosity of 10^{43} erg/s is 10^{51} quanta per second. The calculated flux J_X through the cylinder sidewall will make 10^{31} quanta per square cm per second. Thus, a unit volume of the gas-and-dust aggregate contains in average several hundreds of atoms, 1–2 dust grains and X-ray quanta with the energy of 1 keV of 80 erg or $8 \cdot 10^{10}$ photons in total. Each of these dust grains is comprised of 10^6 atoms in average. When substituting the specified data into formulae (4) and (5), we obtain that at the distance of 200 pc each X-ray and γ-quanta are thermalized in the interstellar gas. In dust this process occurs on a scale of several tens of parsecs. The averaged combined contribution of gas and dust yields the maximum effect not exceeding a hundred of parsecs. Satellite observations in the X-ray band have shown the presence of diffuse X-ray halos in the regions wherein the hard radiation fluxes are formed in the vicinity of the centres of AGN and a number of other point-like objects. This type of coherent scattering is called anomalous diffraction. In the examined media, this type of scattering adds noticeably to the diffuse X-ray and ultraviolet background. The dielectric permittivity in the X-ray band is close to 1 (Weingarter and Draine, 2001) .

Alongside anomalous diffraction, X-ray and UV quanta are scattered at small, close to 90 degrees angles with the tangent to the surface. The fraction of scattered quanta makes up to 10–20% of the total flux. Additional sources of energy are required to reach the diffuse optical luminosity of AGN measured on the basis of the relevant catalogue data on the AGN luminosity in the optical band. Fluxes of protons and α-particles with energies up to 1–3 GeV may serve as such extra sources. However, particles of such energies have an effect on the peripheral regions of AGN through cascade reactions induced by the so-called Δ-resonance. The relative fractions of the products of such cascades in question are as follows: 50% of positrons, 25% of electrons and 25% of photopions. The final energies of leptons which are also products of these series of reactions, reach several tens of MeV; and leptons effectively lose their energy due to ionisation in gas and dust. When high-energy protons and α-particles directly hit dust grains, they are very likely to pass through them. The energy transferred to a dust grain through a series of quantum processes will be spent for its heating, evaporation, photoemission, modification of its crystalline lattice structure and own radiation. This is why it is only particles of the smallest sizes inducing coherent scattering of the soft X-ray and hard UV radiation that can exist in the near-surface layer in the periphery of AGN.

5 Discussion

It is not only condensation of dust grains that is affected by the hard radiation field, but also their final size distribution $N(a)$. In this paper, we also detected a correlation between $N(a)$ and surface potential of dust grains $\varphi(\alpha)$. Therefore, we ultimately obtain the function $\varphi(\alpha, E)$ where E is the energy of CR or hard quanta. In this case,

we expect increased relative content of electrons in the dusty medium, as well as increased content of charged ions, atoms, molecules and particles even in the interstellar medium with lowered abundance of ions. Due to the aforementioned factors we observe increased temperature of the interstellar gas. Unlike thermal electrons, the Auger electrons are not involved in the ion recombination. They mainly contribute to the excitation of practically all electron shells. We assume that the coefficient of the Auger-electron energy transfer to the atomic or molecular electron shells is 0.1%, and this is one of the sources of the optical luminosity produced by AGN.

Tailing off the large end of the size distribution of dust grains $N(a)$ results in increased fraction of the scattered X-ray emission at the energies ranging within 1–10 keV, and consequently in higher diffuse luminosity of AGN and supernova remnants. As reported in [6], the main effect of the CR fluxes comes down to the emission of the soft X-ray quanta induced by the cascade transitions to the K-shell vacancies in atoms, molecules and dust grains. The quanta thus produced also undergo coherent scattering over micro particles. Therefore, we can conclude that atoms, molecules and dust grains manifest themselves simultaneously in the soft X-ray band at 0.1–10 keV. A thicket of cascade transition lines which are of interest with regard to the identification of chemical elements has been observed in the specified spectral region. With respect to the classification by energy, the observed transitions are quite distant from each other in terms of their identification. This indicates that the correlation between the luminosities observed in the γ-ray, soft X-ray and optical bands make it possible to develop a new pattern of the physical processes inside gas-and-dust aggregates embedded in the field of hard radiation and CR.

6 Conclusions

In this study, we have determined the effects of the hard radiation field and high-energy particles on the electrophysical and spectroscopic properties of the mixture of gas and dust. When such aggregates are localised in the supernova remnants and AGN, they produce distinctive spectroscopic effects which can be used to identify relevant physical processes with characteristic radiative feedback upon the exposure to these types of radiation at different energy intervals. In this case, diffuse X-ray and optical emission have the origin described in this paper and are associated with certain specific processes. According to (Fan et al., 2016), there is a correlation between γ-ray, X-ray and optical fluxes in a number of classified BL Lac type galaxies. The reported data and methods are extended with the correlation between fluxes in the X-ray and IR spectral regions of young supernova remnants (Dwek et al., 2008). During the last two decades, the X-ray and IR fluxes have increased and then decreased proportionally. The dust temperature and IR flux emitted from AGN can be estimated by the emission flux at the energy of 1 keV and known chemical composition of dust grains. The correlation between incident hard radiation and optical radiative feedback of AGN is based on some other physical mechanisms which are partially described in this paper and in (Doikov et al., 2019c,d) – namely, the combined effect of high-energy CR and hard radiation from the jet at the centre of AGN. The plotted AGN size distribution of dust grains $N(a)$ exhibits a δ-shape decline down to $a = 30$ nm. It means that without compromising the accuracy all particles

can be considered as evenly distributed within the range of 10–20 nm. Under certain conditions, photoemission from the surface of small particles and seed condensation nuclei leads to an increase in the surface potential up to a critical value. Exceeding the critical potential of particles may result in the Coulomb explosion of some small particles. This process is governed by the intensity of hard radiation and reverse flux of electrons from the interstellar medium surrounding the particle.

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