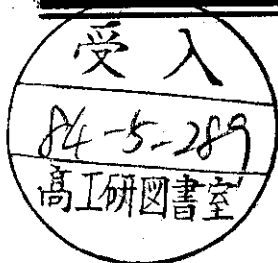


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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ



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RELATIVISTIC ELECTRON-PHOTON SHOWERS IN COMPACT
X-RAY SOURCES

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Ф. А. АГАРОНЯН, В. В. ВАРДАНЯН,* В. Г. КИРИЛЛОВ-УТРУМОВ*

РЕЛЯТИВИСТСКИЕ ЭЛЕКТРОННО-ФОТОННЫЕ ЛИНИИ
В КОМПАКТНЫХ РЕНТГЕНОВСКИХ ИСТОЧНИКАХ

Выдвигается гипотеза, что наблюдаемое гамма-излучение активных галактик и квазаров обусловлено развитием высокоэнергичного каскада в источниках активности. Рассматривается возможность объяснения скорости образования позитронов в центре Галактики. Обсуждается природа "избытка" мягкого гамма-излучения в спектре рентгеновского источника Лебедь X-1.

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A hypothesis is suggested that the gamma-ray emission of active galaxies and quasars is due to the development of high-energy electromagnetic cascade initiated by nonthermal relativistic particles on the ambient X-rays in the central power sources. A possibility to explain the positron production in the Galactic Center in the framework of the "cascade" model is considered. The nature of the MeV excess in the spectrum of Cygnus X-1 is discussed.

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In our previous paper [1] we have investigated the development of the electromagnetic cascade initiated by the relativistic electrons and gamma-rays in the radiation-dominated plasma. In the present paper we discuss a possibility of production of the relativistic electron-photon showers in compact X-ray sources.

1. Nuclei of Active Galaxies and Quasars

At present, it is established reliably that the explosive phenomena in active galaxies are connected directly with the activity of their nuclei. Although the principal indications of the activity of the galactic nuclei are formulated by Ambartsumian as far back as 1958 [2], the nature of the power sources is however vague in many respects up to now (see, e.g. [3]). Any model that claims as to explain the nature of active galactic nuclei must provide high luminosity (up to 10^{47} erg/s in quasars), short time variability ($\leq 10^7$ s), and relatively long lifetime ($\sim 10^7$ yrs) of these objects. Three models of nuclei of active galaxies are considered at present as most appropriate ones: a massive accreting black hole, a massive spinar

(magnetoid), and a dense star (pulsar) cluster. The observation data available do not, unfortunately, allow to choose unambiguously between these models, and the more so to construct a non-contradictory theory of the nuclei of active galaxies and quasars. In constructing such a theory, a more detailed study of wide spectrum of electromagnetic radiation including X- and gamma-ray ranges seems highly important. Certain hopes are set also on neutrino-astronomy [4].

Incidentally, the observations on specialized X-ray satellites have already made an essential contribution to the extragalactic astronomy. It is established, in particular, that one of the most characteristic features of the active galaxies and quasars is their powerful X-ray radiation. Small timescales of emission variability ($10^2 \pm 10^7$ s) combined with high luminosity strongly suggests that the X-rays are produced directly near the power sources. For a number of the nearest active galaxies, particularly for Cen A and NGC 4151, on the observatory "Einstein" the direct evidence are obtained that the main portion of the observed soft X-rays is originated in the compact regions coinciding with the nuclei of these galaxies.

The HEAO-1 spectral observations of active galaxies have shown that the spectra of the active galaxies extend up to the hard X-ray region, the mean active galaxy spectrum created from the individual galaxy spectra, is best-fit in the range 2-120 keV by a power-law of index 1.62 ± 0.04 [5]. Similar hard X-ray spectra are observed also from two nearest quasars 3C 273 and 0241 \pm 622 [6-8]. The power-law character of X-ray spectra of the active galaxies and quasars can be explained satisfactorily in the framework of both synchrotron self-Compton (non-thermal) model and by comptonization of low-frequency photons in accretion plasma around a massive black hole (see, e.g. [9]). If the X-ray photons are produced due to the synchrotron self-Compton mechanism, then the spectrum of the relativistic electrons must be

power-law one with the index $\Gamma_e \approx 2\Gamma_x - 1 \approx 2,2$. Such a spectrum of electrons, according to Lightman, agrees with predictions for shock accelerated electrons in cores of active galaxies. A characteristic feature of the synchrotron self-Compton models is the possibility (at the appropriate choice of the values of magnetic field and injection spectrum of relativistic electrons) of self-consistent explanation of a wide range of electromagnetic spectrum.

The comptonization of low-frequency radiation on thermal electrons of hot plasma results in the formation of the power-law spectrum of photons up to the energy of 3 kT with the subsequent exponential behaviour at $E_x \gg 3 kT$ [10-12]. According to the HEAO-1 data, the mean active galaxy X-ray spectrum is best-fit by the comptonization spectrum at the plasma temperature $kT = 25 \pm 10,2$ keV and electron scattering optical depth equal to $\tau_{es} \approx 4,53 \pm \frac{1,73}{0,94}$ [5]. In the black-hole models of the power source, besides the thermal (comptonized) X-ray component, also the other high-energy component is possible due to acceleration and interactions of the relativistic particles in the accretion plasma. The mechanisms of the particle acceleration in the vicinity of massive black holes were discussed by Kafatos et al. [13]. Gamma-rays can be produced at both inverse Compton scattering of the relativistic electrons on X-rays and decay of secondary π^0 -mesons generated in the inelastic (p-p) collisions. In two-temperature accretion disks [11] some contribution to gamma-radiation can be made also by π^0 -mesons produced in the interactions of thermal protons of accretion plasma with the ion temperature $T_i \sim 10^{12}$ K. However the efficiency of this mechanism of gamma-ray production in accretion plasma is apparently not too high [14].

The extragalactic gamma-radiation from the discrete sources in the range 1 - 10 MeV was discovered for the first time from the radio galaxy Centaurus A

[15] and Seyfert galaxy NGC 4151 [16,17]. The soft gamma-ray luminosities of these galaxies ($\sim 10^{44}$ erg/s and $\sim 10^{45}$ erg/s, respectively) exceed more than by an order their luminosities in the other ranges of electromagnetic radiation. The presence of a MeV "bump" in the radiation spectrum is apparently the common property of active galaxies: up to the present time soft gamma-radiation from two more sources (Seyfert galaxy MCG 8-11-11 and quasar 0241+622) are discovered [18-20].

The hard gamma-radiation is discovered from the quasar 3C 273 (≥ 50 MeV) [21], and perhaps from the NGC 4151 and 0241+622 (≥ 100 MeV) [22,23], though the reliability of observations for the last two sources is not too high. As was mentioned above, in the framework of models explaining the X-radiation of nuclei of the active galaxies also the effective production of gamma-radiation is possible. However, because of the extreme compactness of the sources, free escaping of gamma-rays from the production region is practically forbidden if the X- and gamma-rays originate in the same sources. As a result, in the sources the relativistic electron-photon showers are initiated inevitably. Spectra of gamma-rays and electrons escaping from the active region are determined in many respects by the conditions of development of high-energy cascade.

a) The Seyfert Galaxies NGC 4151 and MCG 8-11-11

The X-emission of the Seyfert type 1 galaxy NGC 4151 is characterized by hard power-law spectrum. According to the HEAO-1 data the index of power-law approximation in the energy range 2-120 keV is $\Gamma_X = 1.50 \pm 0.02$ [5]. The X-ray variability of this galaxy has been observed on timescales ranging from 700 s [24] to a few days [25]. In the region of hard X-rays the spectrum somewhat flattens ($\Gamma_X \sim 1$) reaching (1-2) MeV, and further on it

steepens sharply (see Fig.1). The SAS-2 upper limit of gamma-ray flux in the 30-200 MeV range also indicates the presence of cutoff at MeV energies in the spectrum. It should be however noted that the finite flux of hard gamma-rays from NGC 4151 exceeding by an order the SAS-2 upper limit, was reported by Galper et al. [22]. The comparison of the spectrum of the NGC 4151 with those of quasars 3C 273 and 0241+622 points out that the result of [22], despite its insufficient statistical confidence, does not "fall out" noticeably from the assembly of data, and its contradiction with the SAS-2 data is possibly due to the strong variability which takes place, particularly in the MeV region. It follows from the comparison of the results obtained by different groups during 1977-1979 that above ~ 0.5 MeV the flux changes by a factor of 3-10 on a timescale up to 1 yr [27]. At a distance to the source $d \approx 20$ Mpc the mean low-energy gamma-ray luminosity is $\sim 10^{45}$ erg/s, which is essentially higher than in all other electromagnetic wavebands.

In the models NGC 4151 which explain both hard X- and gamma-radiation by the inverse Compton scattering of relativistic electrons, the agreement with the observed spectrum is achieved by certain assumptions on the shape of primary electron spectrum. Schlickeiser [28] has shown that the requirements to the primary spectrum of electrons are minimized in case of their scattering on soft X-ray photons. However the second key assumption on transparency of the production region for gamma-rays in the nonthermal Compton models in case of NGC 4151 is not fulfilled, since the soft X-ray (≤ 10 keV) production region size, as follows from the discovered by Uhuru X-ray flare with a duration of 700 s [24], does not exceed $? \cdot 10^{13}$ cm*.

* Although no more X-ray flares of NGC 4151 were so far observed, however, the fast X-ray variabilities of the Seyfert galaxy NGC 6814 ($\Delta t \leq 10^2$ s) discovered by HEAO-1 [29] and quasar 0X 169 ($\Delta t \leq 10^4$ s) found by Einstein observatory [30] testify on reliability of the Uhuru result [24].

In the thermal models of NGC 4151 it is assumed that the gamma-emission is formed in the hot accretion plasma with temperature $T_e \sim 5 \cdot 10^9 \text{K}$ (see, e.g. [9]), for example, as a result of comptonization [31] or annihilation of electron-positron pairs [32]. In fact, we encounter here the problem of the hot electron-photon "fireball" which apparently takes place in the sources of gamma-ray bursts [33]. Unfortunately, the problem on dynamics and particularly on the emission spectrum of such a "fireball" is not solved so far. Therefore the MeV's "bump" in the spectrum of NGC 4151 can be explained by the radiation of thermal subrelativistic plasma only qualitatively. Moreover, there exists one essential, to our mind, argument against the thermal nature of soft gamma-radiation of NGC 4151, namely, the observed gamma-radiation from the quasars 3C 273 and O241+622, and possibly from NGC 4151 itself, which surely is not associated with the thermal plasma radiation.

We assume that the observed gamma-ray emission of NGC 4151 is a result of the development of the relativistic electron-photon showers in the active region coinciding with the X-ray production region. Fig.1 presents the spectra of NGC 4151 in the range $10^2 - 10^5 \text{keV}$ calculated within the "cascade" model. The calculations were done for the spherical geometry of the source. The X-ray photon density at a given size of the source R was taken

$$n_x(E_x) = \frac{4\pi d^2 \Phi(E_x)}{4/3 \pi R^2 c} (1 + \tau_{es});$$

where $\tau_{es} = \sigma_T \cdot R \cdot n_e$ is the electron scattering optical depth, n_e is the plasma electron density, $\Phi(E_x)$ is the observed flux of the X-rays, d is the distance to the source.

The X-ray emission of NGC 4151 up to the 100 keV energy is satisfacto-

rily explained by both synchrotron self-Compton mechanism (then the density of thermal electrons n_e and correspondingly τ_{es} may be considered negligibly small) and comptonization of low-frequency photons in accretion thermal plasma. The histograms correspond to the case when the hard X-rays are produced at scattering of relativistic electrons on their own synchrotron photons, and the cascade is initiated by primary electrons with the power law spectrum in the range 50-5000 MeV with the index $\sqrt{E} = 2\sqrt{x} - 1 \approx 2$. The comparison of these histograms with the experimental data shows that at the source's size $R \geq 10^{15}$ cm (curve 1) the calculated spectra do not agree with the observations in the energy region above 100 MeV. At smaller sizes of the source the yield of high-energy photons is suppressed due to photon-photon collisions ($\tau_{\gamma\gamma} \approx (R/10^{15} \text{ cm})^{-1}$ at $E_\gamma = 100$ MeV). In particular, at $R = 10^{14}$ cm a satisfactory agreement of the theoretical spectrum (curve 2) with the observations is achieved, the transformation of primary electron energy into high-energy photons being very efficient ($\geq 70\%$).

The photon spectrum initiated also by primary gamma-rays with $E_{\gamma 0} = 100$ MeV in plasma with electron temperature $kT = 30$ keV and $\tau_{es} = 4$ is given for $R = 10^{14}$ cm (curve 3). It is also assumed that the X-ray photons up to 100 keV are formed due to comptonization, and initial gamma-rays are produced from the decay of secondary π^- -mesons. π^- -mesons may produce in inelastic collisions of thermal nucleons of plasma with ion temperature $T_i \sim 10^{12}$ K. More effective is the production of π^- -mesons at interactions of accelerated in accretion plasma protons with ambient thermal particles [4, 34]. In this case, together with gamma-rays and electrons also accompanying high-energy neutrinos (> 1 TeV) are produced. Using the calculations of Berezhinsky and Ginzburg [4] on the yield of gamma-rays and accompanying neutrinos in (p-p) interactions and taking into account

that nearly 70% of energy of secondary (from π^- -decays) electrons, positrons and gamma-rays transform into photons of the energy ≤ 3 MeV, one can obtain the expected flux of neutrinos from NGC 4151 provided the model of Berezhinsky and Ginzburg [4] be realized. Thus for the power-law spectrum of accelerated photons with index $\Gamma_p = 2.3$:

$$\Phi_{\nu} (> 1 \text{ TeV}) \approx 100 \text{ neutrinos/m}^2\text{yr},$$

and for $\Gamma_p = 2.6$ it is approximately by one order less. Such fluxes can be measured by proposed DUMAND array.

Note that a characteristic size of the source $\sim R \approx 10^{14}$ cm in the "blackhole" models, where the main energy release of accretion gas occurs at a distance $10 R_g$ ($R_g = \frac{2GM}{c^2} \approx 3 \cdot 10^{13} (M/10^6 M_\odot)$ cm is a gravitational radius), corresponds to the mass of black hole $M \sim 10^6 M_\odot$ and hence about 10% of Eddington luminosity $L_{\text{Edd}} = \frac{29 R_g m_p c}{\sigma_T} \approx 10^{46}$ erg/s is to be released in X- and gamma-rays.

Note that the observed luminosity 10^{45} erg/s of NGC 4151 sets a lower limit on the central black hole mass: $M \geq 10^7 M_\odot$. On the other hand, from the observed X-ray rapid variability (~ 700 s) it follows that if the radiation is produced in the inner zone of accretion disk, then the black hole mass does not exceed $10^7 M_\odot$. More precise calculations, with account of radiative transport effects yield a lower value $M \leq 6 \cdot 10^6 M_\odot$ [24]. This means that if the central accreting black hole is the power source of NGC 4151, then the soft X-rays are produced outside the region of the main energy liberation, i.e. at a distance $R \gg 10 R_g$. The observed intensity increase by a factor of 5-10 on a timescale of ~ 700 s is probably the result of local X-ray burst.

Do the hard X-rays and gamma-rays really form in that "hot spot" and are they, hence, the manifestation of local activity? The calculations of

the cascade in the region of $2 \cdot 10^{13}$ cm size filled by soft X-rays (≤ 10 keV) yield hard power-law spectra of gamma-rays up to 50 MeV, which contradict obviously the observations. Formally, one may achieve more or less satisfactory agreement, assuming that also the observed X-ray photons up to 100 keV originate in this "hot spot". However this assumption disagrees with the model-independent relation between the X-ray luminosity L_x and timescale of variability Δt [9]

$$L_x / (\eta \Delta t) \leq 2 \cdot 10^{42} \text{ erg/s}^2$$

where η is the efficiency of the matter conversion to the radiation.

For $\Delta t \sim 700$ s and X-ray luminosity, in the range 2-120 keV, $5 \cdot 10^{43}$ erg/s, we arrive at a requirement for $\eta \geq 0.03$, which even in the "black-hole" models (taking into account that the radiation is produced outside the zone of main energy release) seems somewhat problematic.

It follows from the calculations that the best agreement of the theoretical spectra with the observations is achieved at the active region sizes $R \approx 10^{14} - 3 \cdot 10^{14}$ cm. Unfortunately, most of the measurements given in Fig.1 are attributed to different times of observations, therefore the further verification of the cascade parameters will be possible only at availability of data to be obtained simultaneously in wide energy range.

Recently, the soft gamma-emission was discovered from the Type 1 Seyfert galaxy MCG.8-11-11 [18]. The observed spectral feature at MeV energies, namely steepening of the spectrum, is highly similar to that of NGC 4151. The X-ray emission of this source up to the energy 20 keV is well approximated by a power-law spectrum with the index $\Gamma_x = 1.6^{+0.3}_{-0.2}$ [35]. The luminosity in this range is 10^{44} erg/s. In the hard X-ray region (≥ 20 keV) the data of the HEAO-1 and balloon experiments disagree with

each other, which apparently is connected with the radiation variability. X-ray variability of the source on a timescale ≤ 30 days has been reported

Fig. 2 presents the spectra of gamma-ray emission of MCG 8-11-11 calculated within the "cascade" model. It was assumed in the calculations that the cascade is initiated by the relativistic electrons, that possess the initial spectrum with the index $\Gamma_e = 2$ in the range 50-5000 MeV, in the field of 2-20 keV photons. For a characteristic size of the active region $R = 10^{14}$ cm, the agreement of the theoretical spectrum (curve 1) with the observed one up to the hard gamma-ray range, where the upper limit of the flux is obtained by SAS-2, may be considered satisfactory. At the same time, an obvious disagreement between the calculated (curve 2) and observed spectra is encountered at $R = 10^{15}$ cm. The disagreement can be "smoothed away" assuming the initial electron spectra are steeper, or admitting that the observed in the range ≤ 20 keV spectrum of X-ray photons extends up to the hard X-ray region (~ 100 keV), which, in particular, takes place in NGC 4151. Note that the size $\sim 10^{15}$ cm from the energetic viewpoint is more advantageous for MCG 8-11-11 possessing gamma-ray luminosity

$L_\gamma \sim 7 \cdot 10^{46}$ erg/s. In particular, for the accretion disk model, this size corresponds to the central black hole mass $\geq 10^9 M_\odot$ and respectively to the critical luminosity $\geq 10^{47}$ erg/s.

b) The Quasars 3C 273 and 0241+622.

In 1978, the hard gamma-radiation was discovered from the quasar 3C 273 on the COS B satellite. The proton spectrum observed in the range 50-800 MeV is approximated by the power-law with the index

$\Gamma_\gamma = 2.5^{+0.6}_{-0.3}$ [21]. 3C 273 is also a powerful X-ray emitter with a power-law spectrum with $\Gamma_x = 1.68 \pm 0.14$ up to 120 keV [6,7]. The QSO's

X- and gamma-ray luminosities at a cosmological distance to the source $d = 360$ Mpc ($z = 0.158$, $H_0 = 55$ km/s Mpc) are $7 \cdot 10^{46}$ erg/s and $3 \cdot 10^{46}$ erg/s, respectively.

The QSO is variable in the X-rays. It was reported on variability in the 2-60 keV region on timescale of about months [36]. The variability in the essentially shorter timescale ($5 \cdot 10^4$ s) was discovered on the Einstein observatory in the soft X-rays [37]. This testifies to compactness of the X-ray source (sources?), and hence large optical depth of the X-ray production region to photon-photon collisions [21, 38].

The development of the relativistic electron-photon cascade shower in the 3C 273, assuming that both the hard X-rays and gamma-rays originate from the same region, was considered for disc spherical geometry with the purpose to study the possibility of the coincidence of X- and gamma-ray production regions. Fig.3 shows the spectra of the gamma-ray emission emerged from the source for spherical geometry and for monoenergetic (with $E_{\gamma 0} = 200$ mc²) and power-law (with $\Gamma_{\gamma} = 2$) spectra of initial gamma-rays. It follows from the calculations that at $R \ll 10^{17}$ cm the major portion of the initial gamma-ray energy transform into photons with ≤ 5 MeV energy, for which the source turns out transparent (curve 1). In this case the result weakly depends on the geometry and initial gamma-ray spectrum. Thus we can claim that the hard gamma-radiation is produced far from the variable Einstein observatory soft X-ray source (0.5 - 3.5 keV), whose size, as it follows from the short term variability, does not exceed 10^{15} cm.

From the $R \geq 10^{17}$ cm, an efficient release of gamma-rays with $E_{\gamma} \geq 5$ MeV also becomes possible (curve 2). As $\tau_{\gamma\gamma}$ is yet greater than unity (~ 10 at $R = 10^{17}$ cm), an essential transformation of the initial spectrum occurs as before. Thus, for $R = 10^{17}$ cm and the production

power-law spectrum with $\Gamma_\gamma = 2$, the resulting spectrum of escaping photons with $E_\gamma \geq 50$ MeV has an approximate power-law dependence with an index $\Gamma_\gamma = 2.5$ (curve 3) being in agreement with the COS B data [21]. Note that a similar result can be obtained in case when the cascade is initiated by the relativistic electrons. Then approximately 10% of the total energy stored in the initial particles remain in the hard gamma-rays with $E_\gamma \geq 50$ MeV. Hence we obtain a requirement for a necessary power of the energy reservoir $\sim 3 \cdot 10^{47}$ erg/s to explain the observed flux of hard gamma-rays. Approximately a half of this luminosity is released in the range of soft gamma-rays. For comparison we point out that in all other electromagnetic wavebands (from radio up to hard gamma-rays) the luminosity of 3C 273 is $2.5 \cdot 10^{47}$ erg/s [39]. Unfortunately, there is no so far information on 3C 273 in this, perhaps most important (from the viewpoint of energetics) range of soft gamma-rays, which does not permit to conduct further verification of the cascade parameters. The quasar 0241+622 is, in this sense, more "informative".

The search of X-ray emission from unidentified COS B gamma-ray sources has shown that the X-ray source 4U 241+61 from the 4-th Uhuru catalog falls into the error circles of the gamma-ray source CG 135+1 [40]. Later on, the X-ray source was identified reliably with the nearest quasar 0241+622 [41]. Because of relatively large error box for the gamma-ray source CG 135+1, the question on the identification of the latter with the quasar 0241+622 is left open. Some more objects besides the quasar 0241+622, in particular the highly variable radio source GT 0236+61 [42] being at a distance ~ 2.5 kpc, fall into the error box of CG 135+1.

Fig.4 shows the observed spectrum of the quasar 0241+622 admitting that CG 135+1 \equiv 4U 241+61 \equiv 0241+622. For such a hypothesis, besides the argument

of great similarity of the quasar 0241+622 with the quasar 3C 273 possessing hard gamma-ray emission, there exists, to our mind, one more important evidence, namely the observed soft gamma-ray emission in the direction of CG 135+1 [19,20]. By that, CG 135+1 differs from the other unidentified COS B sources [23] and may resemble the nuclei of active galaxies.

Fig.4 gives together with the observed spectrum of the QSO 241+622 the calculated within "cascade" model the spectra of gamma-rays for two cases: 1) the cascade is initiated by the relativistic electrons with the primary power-law spectrum with $\Gamma_e=2$ ($50 \leq E_e \leq 5000$ MeV) in a "pure" X-ray gas ($\Gamma_x = 1.9$; $2 \leq E_x \leq 100$ keV [8]); 2) the cascade is initiated by gamma-ray with $E_\gamma = 500$ MeV in the accretion plasma with $KT = 20$ keV and $\zeta_{es} = 4$. The best fit with the experimental data is achieved at a characteristic size of the active region $R = 3 \cdot 10^{15}$ cm (----) and $R = 10^{16}$ cm (—) for the cases 1) and 2), respectively.

c) The Radio Galaxy Centaurus A/NGC 5128

The spectrum of X-ray emission of the radio galaxy Cen A/NGC 5128 is similar to that of the active galactic nuclei. As in the case with the Seyfert galaxies NGC 4151 and MCG 8-11-11, the spectrum of Cen A extends up to the region of soft gamma-rays where the luminosity reaches its maximum [15,43]. Therefore, by analogy with the above-considered sources, the spectrum of Cen A can be explained by the cascade development near the central power source with the characteristic size $R = 10^{14}$ cm. At the same time the radiation of this radio galaxy has singularities that make it different from the other active galaxies. In the first place it concerns the ultra high energy gamma-rays (≥ 300 GeV) [44] and also the spectral features near 1.6 MeV and 4.6 MeV [15] found in the direction of Cen A.

Within the developed here "cascade" model, the presence of ultra high energy gamma-rays in the emission spectrum is quite naturally explained by the dependence of the photoproduction cross section on the parameter $\beta = \frac{E_x E_\gamma}{m^2 c^4}$ ($\sigma \sim \frac{\ln \beta}{\beta}$ at $\beta \gg \beta_{min}$, $\beta_{min} = 2$), owing to which the compact X-ray source, being thick for gamma-rays of moderate energies, turns out transparent for photons of ultra high energies.

At the same time, gamma-ray lines cannot apparently be explained by the relativistic electron-photon showers. Though, if these lines are real, then any model of gamma-lines formation which is under discussion at present, encounters extremely serious energetic difficulties [45-47].

In the consideration of the development of the electromagnetic showers we here restricted ourselves to only the questions dealing with the production of hard X- and gamma-ray emission. The problem of the formation of non-thermal radio and optical radiation of galactic nuclei and quasars is beyond the scope of this work. It should nevertheless be noted that the observed very small measures of Faraday rotation in many compact extragalactic radio sources are weighty argument in favour of that the radiating particles are an equal mixture of electrons and positrons [48], which is naturally explained by the "cascade" model.

The relativistic electron-positron showers initiated in the low-frequency photon field ($10^{-3} - 10^2$ eV) on external regions of accretion disks around a massive black hole ($M \sim 10^8 M_\odot$) were considered by Burns and Lovelace [49] as applied to double radio sources. However this model gives power-law gamma-ray spectra with constant index up to the energy $E_\gamma \sim 2500$ MeV, which contradicts the gamma-ray emission spectra of the active galaxies.

2. The Compact Source of Positrons at the Galaxy Center

The annihilation radiation at 0.511 MeV observed in the direction of the Galactic Center is being in the focus of attention for already 10 years.

It follows from narrow width of the line ($\Delta E_{\text{FWHM}} \leq 2.5 \text{ keV}$) [50, 51] that it is formed in a partially ionized gas with a degree of ionization

$n_e/n \gg 0.1$ and temperature $T \leq 5 \cdot 10^4 \text{ K}$ [52]. In Refs. [53, 54], strong arguments were adduced in favour of the assumption that annihilation of positrons takes place in the recently discovered warm ionized gas clouds localized within the central parsec of Galaxy around the compact radio source Sgr A* [55]. The discovered or HEAO-3 variability of the line intensity on the timescale of 0.5 yr [51] is in good agreement with that hypothesis.

There are far more uncertainties as concerning the source of positrons. If the source of the observed annihilation line is actually in the central region of the Galaxy and annihilation takes place via intermediate state of the positronium [50], then we obtain the required production rate of positrons assuming a stationary injection to the region of the annihilation line formation:

$$Q_+ = 2 \cdot 10^{43} \text{ s}^{-1}$$

In our previous work [1] it is shown that the positrons may efficiently be produced as a result of the development of the relativistic electromagnetic cascade in hot radiation-dominated plasma with the optical depth to photon-photon collisions $\tau_{\gamma\gamma} \gg 1$. The main requirements following from the analysis of the Galactic Center observations are satisfied in a natural way within the framework of this model: the source compactness ($< 10^{17} \text{ cm}$) [51]; high efficiency of positron production ($L_{0.51}/L_x \gg 3\%$) [50, 56]; evidence for a high-energy cutoff of the spectrum near 1 MeV [56]; relatively low energies ($\leq 20 \text{ MeV}$) of positrons after leaving the source [57].

The presence of X-ray radiation from the compact central region of the Galaxy $L_x = 3 \cdot 10^{38}$ erg/s [50,56] allows us to believe that the development of such a cascade may turn out rather efficient.

Compilation of the observations on hard electromagnetic radiation in the direction of the Galactic Center, as taken from the review by Linnelfelter and Ramaty [53], is shown in Fig.5. The errors for the localization of the source (sources?) of various energy ranges are large as compared with the sizes of the assumed compact object in the center, therefore we may talk only about the upper limit of the X-ray luminosity of the latter. Nevertheless we here assume that the X-ray and gamma-ray emission observed in the direction of the Galactic Center is formed in the compact source, where the production of positrons responsible for the observed annihilation line, also takes place. Just as in the case of active galaxies, we assume that the hard radiation with ≥ 150 keV is formed due to the development of the electromagnetic cascade initiated by the relativistic particles in the X-ray ($E_x \sim 1 - 150$ keV) production region.

In our calculations the absolute normalization to the value of the required power of positron production $\sim 2 \cdot 10^{43}$ s⁻¹ was performed. In this case the value of the characteristic size of the active region filled isotropically with the X-ray photons was varied unless the luminosity of the cascade photon component with $E_x \geq 150$ keV become less or equal to the observed one in the Galactic Center direction $L_x \sim 3 \cdot 10^{38}$ erg/s [50,56]. The calculations show that the best agreement with the observations is achieved at the source size $R = 3 \cdot 10^7$ cm and the injection power of the initiating relativistic electrons $\dot{W}_e = 3 \cdot 10^{38}$ erg/s, the result depending weakly on the initial electron spectrum. About 70% of this power is released in soft gamma-rays with $E_\gamma \sim 1$ MeV, which agrees with the observations (Fig.5). Due to the substantial Compton losses, only an insignificant port-

ion of the produced electron-positron pairs ($\leq 1\%$) leaves the source with relativistic energies. Thus the requirement, that the positrons responsible for the annihilation line enter the region of the line formation having the energies less than ≤ 20 MeV [57], holds, too. Here, apparently, an additional mechanism is needed for the nonrelativistic positrons delivery into the cold annihilation region, say, as a result of the injection from the source under the pressure of radiation.

It is seen from Fig.5 that the luminosity in low-energy photons (≤ 150 keV) produced at the cascade development is essentially less than the prescribed luminosity of the photon target-field, which fact is a criterion of validity of linear approximation ("stationary target" - see [1]) of the cascade development applied in the calculations.

At the source sizes $R > 3 \cdot 10^7$ cm the efficiency of the cascade development is falling down, therefore the power of injection of the relativistic electrons more than $3 \cdot 10^{38}$ erg/s is needed in order to provide the required rate of positron production $Q_+ = 2 \cdot 10^{43} \text{ s}^{-1}$. This automatically leads to gamma-ray luminosity which exceeds the observed one. Note that the restriction for R somewhat "softens" (nearly $(1 + \tau_{es})$ times as much), assuming large electron scattering depth τ_{es} of the target-plasma.

The obtained values of the size of the active region $R \sim 3 \cdot 10^7 (1 + \tau_{es})$ cm and of the necessary power of the relativistic electrons $W_e \sim 3 \cdot 10^{38}$ erg/s can be explained within the model of the cascade development in the hot inner zone of the accretion disk ($\tau_{es} \sim 1$) around a black hole with the mass $M \sim (20 \pm 50) M_\odot$. However, more solid observational evidence are apparently needed for such an important statement.

3. The X-Ray Source Cygnus X-1

For many years, the X-ray source Cyg X-1 has been considered a most probable candidate for a black hole (see, e.g. [58]). The crucial arguments in favour of this hypothesis are the X-ray source compactness and the mass estimate of invisible component of binary system $M \sim 10 M_{\odot}$ exceeding the admissible values for a neutron star.

The X-rays are generally considered to produce in the accretion disk around the black hole, although the possibility of the spherically-symmetric accretion cannot be excluded. Notwithstanding the availability of various models of accretion, most of investigators are solidary with each other that the X-ray emission is formed due to comptonization of low-frequency radiation in hot accretion plasma with the temperature $kT_e = 3 \cdot 10^5$ K and electron scattering depth $\tau_{es} \sim 1$. It follows from the intensity fluctuations that the characteristic size of the X-ray production region by an order of magnitude does not exceed 10-50 gravitational radii at $M = 10 M_{\odot}$.

The analysis of spectrometric data of HEAO-1 shows that the X-ray emission up to 150 keV is approximated perfectly by the comptonization spectrum [12] at a plasma temperature $kT_e = 32.4 \pm 0.4$ keV and optical depth $\tau_{es} = 1.6$ and $\tau_{es} = 3.9$ for disk or spherical geometry, respectively [59]. However a hard component of radiation (≥ 300 keV) observed on the HEAO-1 testifies to the spectrum flattening near 0.5 MeV [59]. Nolan and Matteson [60] assume that the high-energy excess may be interpreted as a broad emission line near 0.5 MeV from the annihilation of the electron-positron pairs in hot accretion plasma.

The most significant mechanism of the electron-positron plasma formation in the accretion disks is pair photoproduction in photon-photon collisions.

However this mechanism for moderate values of optical depth $\tau_{es} \sim 1$ becomes efficient enough only at temperatures $kT_e \geq 100$ keV. At the same time, according to Ichimaru [61], a maximum temperature attained in inner regions of the accretion disk is

$$kT_{\text{max}} \approx 87 (M / 7 \cdot 10^{17} \text{ g/s})^{2/5} (L_x / 1 \cdot 10^{37} \text{ erg/s})^{-2/5} \text{ keV}$$

On the other hand, the temperature $kT_e \geq 100$ keV contradicts the X-ray spectrum.

We here assume that the observed spectral feature at about 500 keV is of nonthermal nature, namely is associated with the development of the cascade initiated by the relativistic electrons in the inner zone ($R \sim (3 \div 10) \cdot R_g \approx (1 \div 3) \cdot 10^7 (M/10 M_\odot) \text{ cm}$) of the accretion flow. In our calculations the plasma temperature $kT_e = 30$ KeV and optical depth $\tau_{e\gamma} \approx 6$ were taken according to the X-ray spectrum. Fig. 6 shows the calculational curves of gamma-radiation from accretion plasma for two values 10^7 cm (----) and $3 \cdot 10^7 \text{ cm}$ (—) as well as for the energy of the initiating electrons 100 MeV. Highly similar results are obtained also in the case of $E_0 = 1$ GeV. The efficiency of conversion of the initial energy of electrons into photons in the region of ~ 0.5 MeV amounts to $\sim 30\%$. From here we get a requirement for the power of accelerated electrons $\dot{W}_e \approx 10^{37} \text{ erg/s}$ to provide the observed flux in soft gamma-rays, which is only 1% of Eddington luminosity of the source ($M = 10 M_\odot$).

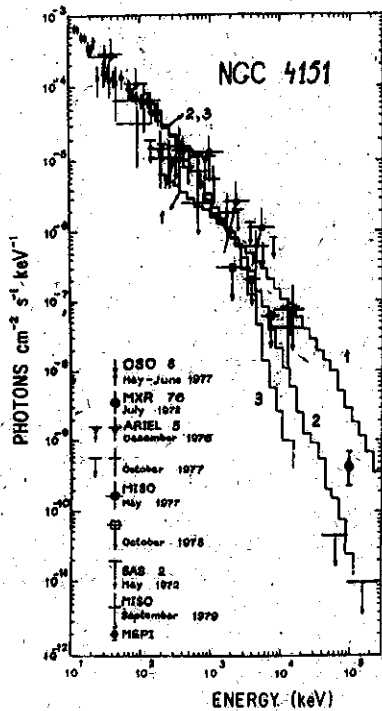


Fig.1

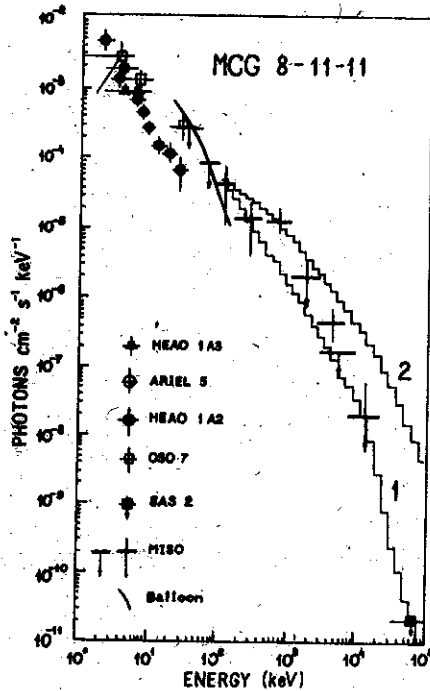


Fig.2

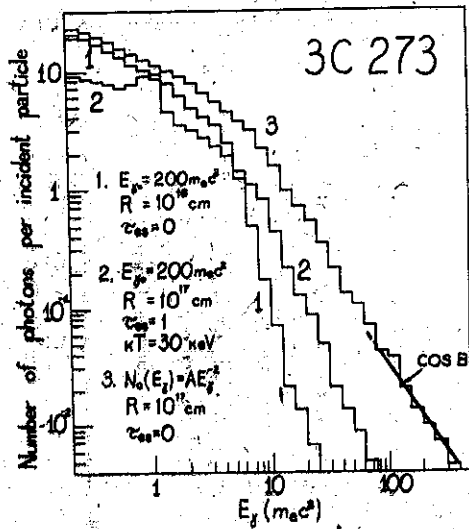


Fig. 3

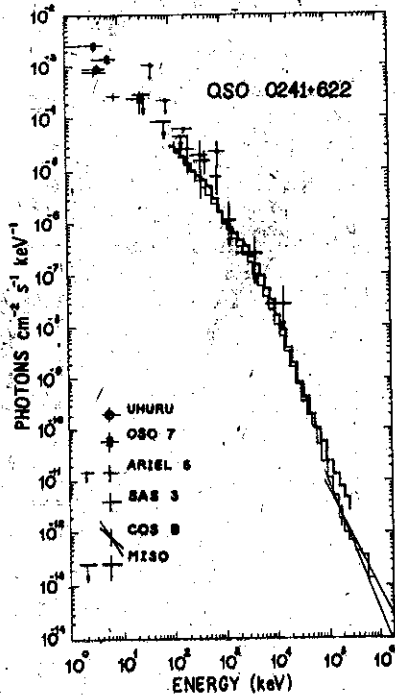


Fig. 4

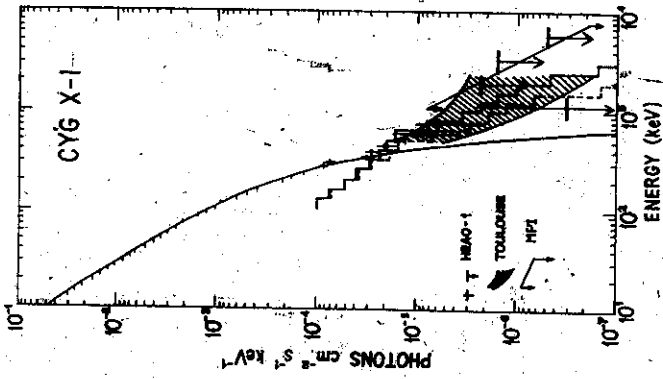


Fig. 6

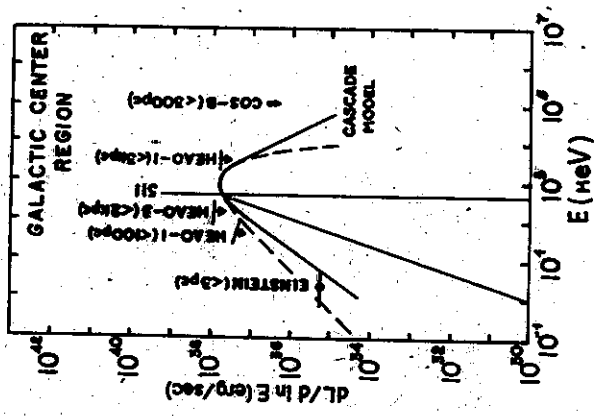


Fig. 5

FIGURE CAPTIONS

Fig.1. The photon spectrum of MCG 4151.

Fig.2. The photon spectrum of MCG 8-11-11.

Fig.3. The photon spectrum of 3C 273.

Fig.4. The photon spectrum of QSO 0241+622.

Fig.5. The luminosity as a function of photon energy from the region around the Galactic Center.

---- "optically thin plasma" model of

Lingenfelter and Ramaty [53]

— "cascade" model:

$$R = 3 \cdot 10^7 \text{ cm and } \dot{W}_e = 3 \cdot 10^{38} \text{ erg/s.}$$

Fig.6. The photon spectrum of Cyg X-1.

REFERENCES

1. Aharonian F.A., Kirillov-Ugryumov V.G., Vardanian V.V. Development of high energy electromagnetic cascade initiated by relativistic electrons and gamma-rays in hot photon gases.- Preprint EPI-676(66)-R3, Yerevan, 1983.
2. Ambartsumian V.A. In: La structure et l'evolution de l'univers, Edition Stoops, Bruxelles, 1958, p.241.
3. Ginzburg V.L., Ozernoy L.M. On the nature of quasars and active galactic nuclei.- *Astrophys. Space Sci.*, 1977, vol.50, p.23.
4. Berezhinsky V.S., Ginzburg V.L. On high-energy neutrino radiation of quasars and active galactic nuclei.- *M.N.R.A.S.*, 1981, vol.194, p.3.
5. Rothschild R.E., Mushotzky R.F., Baity W.A. et al. 2-165 keV observations of active galaxies and the diffuse background.- Preprint UCSD SP-82-23, La Jolla, 1982.
6. Primini F.A., Cooke B.A., Dobson C.A. et al. HEAO 1 observations of high-energy X-rays from 3C 273.- *Nature*, 1979, vol.278, p.234.
7. Pietsch W., Reppin C., Trumper J. et al. High-energy X-ray observations of extragalactic objects.- *Astron. Astrophys.*, 1981, vol.94, p.234.
8. Worral D.M., Boldt E.A., Holt S.S., Serlemitsos P.J. The X-ray spectrum of QSO 0241+622.- *Ap.J.*, 1980, vol.240, p.421.
9. Fabian A.C. Theories of the nuclei of active galaxies.- *Proc. R. Soc. Lond.*, 1979, vol.366, p.449.
10. Katz J.I. Nonrelativistic Compton scattering and models of quasars.- *Ap.J.*, 1976, vol.260, p.910.
11. Shapiro S.L., Lightman A.P., Eardley D.M. A two-temperature accretion disk model for Cygnus X-1: Structure and spectrum.- *Ap.J.*, 1976, vol.204, p.187.

12. Sunyaev R.A., Titarchuk L.G. Comptonization of X-rays in plasma clouds. Typical radiation spectra.- *Astron. Astrophys.*; 1980, vol.86, p.121.
13. Kafatos M., Shapiro M.M., Silberberg R. Extragalactic variable sources and cosmic-ray acceleration near massive black holes.- *Comments on Astrophys.*, 1981, vol.9, p.179.
14. Aharonian F.A., Atoyan A.M. On time evolution of particle distribution function in high-temperature plasmas.- Preprint EPI 634(24)-83, Yerevan, 1983; JETP (in press).
15. Hall R.D., Meegan C.A., Walraven G.D. et al. Detection of nuclear gamma-rays from Centaurus A.- *Ap.J.*, 1976, vol.210, p.631.
16. Di Cocco G., Boella G., Perotti F. Low energy gamma-ray observation of NGC 4151.- *Nature*, 1977, vol.270, p.319.
17. Schonfelder V. Origin of MeV-excess in the energy spectrum of diffuse cosmic gamma-rays.- *Nature*, 1973, vol.274, p.345.
18. Perotti F., Della Ventura A., Villa G. et al. Soft gamma-ray emission from the region of MCG 8-11-11. - *Nature*, 1981, vol.292, p.133.
19. Coe M.J., Quenby J.J., Engel A.R. Hard X-ray observations of cosmic gamma-ray sources.- *Nature*, 1978, vol.274, p.343.
20. Perotti F., Della Ventura A., Villa G. et al. Low-energy gamma-ray emission close to CG 135+1. - *Ap.J. (Letters)*, 1980, vol.239, p.L49.
21. Bignami G.F., Bennett K., Buccheri R. et al. 3C 273 revisited: confirmation by COS B of high energy gamma-ray emission.- *Astron. Astrophys.*, 1981, vol.93, p.71.
22. Гальпер А.М., Кириллов-Угрюмов В.Г., Лучков Б.И., Озеров Ю.В. Обнаружение избыточных потоков гамма-излучения из района Северного галактического полюса. - *Письма в ЖЭТФ*, 1973, т.17, с.265

23. Hermsen W., Swanenburg B.N., Bignami G.F. et al. New high energy gamma ray sources observed by COS B.- *Nature*, 1977, vol.269, p.494.
24. Lightman A.P., Giacconi R., Tananbaum H. X-ray flares in NGC 4151: a thermal model and constraints on a central black hole.- *Ap.J.*, 1978, vol.224, p.375.
25. Mushotzky R.F., Holt S.S., Serlemitsos P.J. X-ray observations of a flare in NGC 4151 from OSO 8.- *Ap.J. (Letters)*, 1979, vol.225, p.L115.
26. Bignami G.F., Fichtel C.E., Hartman P.C., Thompson D.J. Galaxies and gamma-ray astronomy.- *Ap.J.*, 1979, vol.232, p.649.
27. Perotti F., Della Ventura A., Villa G. et al. Detection of a soft gamma-ray emission from the region of NGC 4151.- *Ap.J. (Letters)*, 1981, vol.247, p.L63.
28. Schlickeiser R. Astrophysical gamma-ray production by inverse Compton interactions of relativistic electrons. III. Cutoff effect for inverse Compton spectra applied to the case of the hard X-ray and gamma-ray emission of NGC 4151.- *Ap.J.*, 1980, vol.240, p.536.
29. Tennant A.F., Mushotzky R.E. The absence of rapid X-ray variability in active galaxies.- *Ap.J.*, 1983, vol.264, p.92.
30. Tananbaum H., Avni Y., Branduardi G. et al. Einstein observations of quasars.- *Ap.J. (Letters)*, 1979, vol.234, p.L9.
31. Pozdnyakov L.A., Sobol I.M., Sunyaev R.A. In: "Astrophysics and Space Physics of Soviet Scientific Reviews", ed. R.A. Sunyaev, 1982, N.Y., Harwood Academic Publishers.
32. Bassani L., Dean A.J. An interpretation of the low energy gamma-ray emission from Seyfert nuclei in terms of annihilation radiation from a hot plasma.- *Astron.Astrophys.*, 1983, vol.122, p.33.
33. Cavallo G., Rees M.J. A qualitative study of cosmic fireballs and gamma-ray bursts.- *M.N.R.A.S.*, 1978, vol.183, p.359.

34. Protheroe R.J., Kazanas D. On the origin of relativistic particles and gamma-rays in quasars. - *Ap.J.*, 1983, vol.265, p.620.
35. Muschotzky R.F., Marshall F.E. X-ray observations of the Seyfert 1 galaxies AKN 120 and MCG 8-11-11. - *Ap.J. (Letters)*, 1980, vol.239, p.L5.
36. Worral D.M., Mushotzky R.F., Boldt E.A. et al. The X-ray spectrum of 3C 273. - *Ap.J.*, 1979, vol.232, p.683.
37. Tananbaum H. In: *X-ray Astronomy*, Eds. R.Giacconi and G.Setti, D.Reidel Publ. Comp., 1980, p.291.
38. McBreen B. The Result of limitation of the X-ray source size on gamma-radiation from 3C 273. - *Astron. Astrophys.*, 1979, vol.71, n.L19.
39. Ulrich M.H. 3C 273: a review of recent results. - ESO sci. preprint No.122.
40. Maraschi L., Markert T., Apparao K.M.V. et al. Possible X-ray counterparts of gamma-ray sources. - *Nature*, 1978, vol.272, p.679.
41. Apparao K.M.V., Bignami G.F., Maraschi L. et al. 4U 0241+61: a luminous low-redshift QSO. - *Nature*, 1978, vol.273, p.450.
42. Gregory P.C., Taylor A.R. New highly variable radio source, possible counterpart of gamma-ray source CG 135+1. - *Nature*, 1978, vol.272, p.704.
43. Baity W.A., Rothschild R.E., Lingenfelter R.E. et al. Centaurus A (NGC 5128) at 2 keV-2.3 MeV: HEAO-1 observations and implications. - *Ap.J.*, 1981, vol.244, p.429.
44. Grindlay J.F., Helmken H., Handbury R. et al. Evidence for the detection of gamma-rays from Centaurus A at $E = 3 \cdot 10^{11}$ eV. - *Ap.J. (Letters)*, 1975, vol.197, p.L9.
45. Lingenfelter R.E., Higdon J.C., Ramaty R. In: *Gamma-ray spectroscopy in Astrophysics*, Eds. T.L.Cline and R.Ramaty (NASA-T.M. 79619), 1978, p.252

46. Ozerney L.M., Aharonian F.A. Nuclear gamma-ray lines from Cen A: evidence for their origin in relativistic plasma.- *Astrophys. Space Sci.*, 1979, vol.66, p.497.
47. Aharonian F.A., Sunyaev R.A. The emission in gamma-ray lines, nuclei destruction and neutron production in hot astrophysical plasmas. Deuterium Boiler as a source of gamma-radiation.- Preprint EFI-583(70)-82, Yerevan 1982; M.N.R.A.S. (in press).
48. Noerdlinger P. Positrons in Compact Radio Sources.- *Phys.Rev.Lett.*, 1978, vol.41, p.135.
49. Burns M.L., Lovelace R.V.E. Theory of electron-positron showers in double radio sources.- *Ap.J.*, 1982, vol.262, p.87.
50. Leventhal M., MacCallum C.J., Stang P.D. Detection of 511 keV positron annihilation radiation from the Galactic Center direction.- *Ap.J. (Letters)*, 1978, vol.225, p.111.
51. Riegler G.R., Ling J.C., Mahoney W.A. et al. Variable positron annihilation radiation from the Galactic Center region. - *Ap.J. (Letters)*, 1981, vol.248, p.113.
52. Bussard R.W., Ramaty R., Drachman. The annihilation of galactic positrons.- *Ap.J.*, 1979, vol.228, p.528.
53. Lingenfelter R.E., Ramaty R. In: *Galactic Center*, Ed. G.R. Riegler and R.D.Blanford, N.Y., AIP, 1982.
54. Озерной Л.М., Шишов В.И. Облака ионизованного газа и природа видимой переменности компактного радиосточника в центре Галактики. - *Письма в АЖ*, 1982, т.8, с.275
55. Lacy J.H., Townes C.H., Geballe T.R., Hollenbach P.J. Observations of the motion and distribution of the ionized gas in the central parsec of the Galaxy.- *Ap.J.*, 1980, vol.241, p.132.

56. Matteson J.L., In: Galactic Center, Ed. G.R.Riegler and R.D.Stanford, N.Y., AIP, 1982.
57. Агаронян Ф.А., Атоян А.М. К вопросу о происхождении галактического аннигиляционного излучения. - Письма в АЖ, 1981, т.7, с.714
58. Eardley D.M., Lightman A.P., Shakura N.I., Shapiro S.L., Sunyaev R.A. A status Report on Cygnus X-1. - Comments on Astrophys., 1978, vol.7, p.151.
59. Nolan P.L., Gruber D.E., Knight F.K. et al. Hard X-ray spectrum of Cygnus X-1. - Nature, 1981, vol.293, p.275.
60. Nolan P.L., Matteson J.L. A possible positron annihilation line. - Ap.J., 1983, vol.265, p.389.
61. Ichimaru S. Bimodal behavior of accretion disks: theory and application to Cygnus X-1 transitions. - Ap.J., 1977, vol-214, p.840.

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РЕЛЯТИВИСТСКИЕ ЭЛЕКТРОННО-ФОТОННЫЕ ЛИНИИ
В КОМПАКТНЫХ РЕНТГЕНОВСКИХ ИСТОЧНИКАХ
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