THE ELECTRON-POSITRON CAULDRON AND THE FORMATION OF THE HARD RADIATION OF QUASARS AND AGN

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Active Galactic Nuclei (AGN) and quasars have unique physical parameters among all the objects in the Universe. Undoubtedly it is the uniqueness of the physical conditions in these systems that gives rise to the peculiar physical processes in them.

It is the compactness of these objects - the large ratio of luminosity to size - that is, probably, their most striking and well known feature. The lower limit on the compactness L_{hard}/R in AGN ranges from 10^{26}-10^{29} erg s^{-1} cm^{-1}. (Here R is determined through the characteristic time t of the luminosity variability R = ct). On the other hand, if one assumes that the luminosity is of the order of the Eddington luminosity, and the dimensions of the radiating region are some few gravitational radii then $L_{hard}/R = 10^{32}$ erg $s^{-1}cm^{-1}$.

Such an extreme compactness leads invariably to $e^{\pm}$ pair production due to photon-photon interactions. The processes which involve electron-positron pairs seem to be among the main ones that crucially influence the formation of X- and γ -radiation spectra in quasars and AGN.

Indirect evidence about the presence of $e^{\pm}$ pairs in these objects comes from the discovery of the annihilation line from the centre of our Galaxy, where a less powerful version of quasar's and AGN's energy generator may be working. From these observations we can estimate the effectiveness of the $e^{\pm}$ pair generating mechanism. It turns out that the ratio of the rest mass energy of the generated $e^{\pm}$ pairs to the total energy released should be no less than 10^{-3}, or greater. The greater the ratio for a model, the easier it is for the model to describe the observational data.

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Furthermore, some of the details of the X- and γ -spectra of AGN and quasars seem to tell us that these hard spectra are probably not of thermal origin. This seems natural in those models in which the energy source in AGN and quasars is a massive black hole rotating in an external magnetic field. Such a black hole operates as an electric battery which accelerates charged particles. In the models being discussed in this paper, it is assumed that the emission from AGN and quasars in the hard part of the spectrum originates due to reprocessing of the energy of particles accelerated to relativistic velocities.

The crucial point in these models is the $e^{\pm}$ pair creation. The most effective mechanism of $e^{\pm}$ pair creation is the $\gamma + \gamma \rightarrow e^{+} + e^{-}$ reaction. Besides this reaction $e^{\pm}$ pairs can be created by the interaction of γ-photons with matter. Novikov and Stern (1985) describe the method of numerical simulation of the physical processes for these models in which $\gamma + \gamma$ reaction is the main source of the $e^{\pm}$ pairs, and discuss the results of these simulations. In the present paper we shall discuss our new results on these models. The alternative model in which γ + matter reaction is used to produce $e^{\pm}$ pairs and to form the hard spectrum was discussed by Kardashev et al., (1983). We do not give here a complete list of references. They can be found in Novikov and Stern (1985) and in the excellent review by Svensson (1985) (see also Blandford, 1986; Rees, 1986; Zdziarsky and Lightman, 1985).

Let us consider models of the first type. By now many models of this kind have been constructed starting with the well known work of Bonometto and Rees (1971). A typical representative of such a model is the following (Svensson, 1985): hard particles with energy $\varepsilon = 2.7 \quad 10^{4}$ (in units of $m_e c^2$) are injected into a region filled with soft photons with $\varepsilon = 2.7 \quad 10^{-5}$ (e.g., due to thermal radiation from an accretion disk). Then a variety of cascade processes involved are investigated, and the resultant spectrum of photons which will be observed is calculated.

Our main idea was to develop the simplest self-consistent model with the least possible number of assumptions, which would explain the observational data. Furthermore, the observational predictions in the model should not be a result of a fine tuning of some parameters but must be a natural consequence of the model's general fundamental properties.

Let us summarize briefly and schematically the main set of observational data on the hard radiation from AGN and quasars, which any model should explain.

1) in the X-ray region (up to 100 KeV) the spectral index α of AGN seems to be "universal" and $\alpha_x \approx 0.7 \pm 0.15$(Rothschild, et al., 1983; Petre et al., 1984). Quasars exhibit wider variations of the index α around the value $\alpha \approx 1$.

2) In some cases, e.g., NGC 4151, there is a cut off in the spectrum at energies of the order of MeV. There is an indication that this cut off is a general feature of AGN spectra (see Bignami et al., 1979).

A cut off of the same type is seen in the spectrum of the centre of our Galaxy. In this case, when the annihilation line has sufficient intensity, an increase in radiation at energies of a few MeV and then a cut off at higher energies is observed.

Here we deal with the following model. (For details see Novikov and Stern, 1985.)

1) We assume that in the centres of quasars, the charged particles are being accelerated. The details of the mechanism of such acceleration are not important.

These particles are injected with some pitch angle into the magnetic field region. Alternatively, the energy could be injected in the form of hard γ quanta which could be created by accelerated particles due to curvature radiation or inverse Compton scattering.

After that we provide a numerical simulation, by the Monte-Carlo method, of all processes in this region without any additional assumptions. We call this region - the $e^- e^+$ cauldron. In this region the processes of multi-particle creation and interaction occur, and we take all of them into account. It should be emphasized that our model does not involve any other particles or radiation sources besides those primarily injected. The problem is solved in a completely self-consistent manner.

We calculate the evolution with time of the photon spectra and the energy distribution of $e^{\pm}$ pairs.

Our final purpose is to demonstrate that in the case of large optical depths (τ) of the whole $e^{\pm}$ cauldron the photon spectrum evolves to some specific shape with a cut off near 2 MeV and a power-law slope at energies <100 KeV. This spectrum is to be confronted with the observational data.

We have studied the dependence of the spectrum on the parameters of the electron-positron cauldron and have shown that for a wide range of these parameters the photon spectrum approaches a "universal" form which is the one observed from AGN and Quasars.

In our model, the injected γ-rays interact with soft photons producing high energy pairs. The soft photons can arise as synchrotron radiation from pairs produced before. Multiple interactions of $e^{\pm}$ with the magnetic field and photons and of photons with photons lead to a cascade increase in the number of particles. The energy of hard particles diminishes until electrons and positrons become semi-relativistic and all photons with energy $> m_e c^2$ are converted into pairs or scattered into the soft region. The particle spectra should relax to a rather soft quasi-equilibrium shape, and further evolution of the system should be much slower than the energy degradation. Our method of numerical modelling of the $e^{\pm}$ cauldron is described in Stern (1985). We recall here the main idea.

Numerical simulation of a realistic steady state cauldron would be rather difficult. The energy injected at a constant rate into the centre of the cauldron spreads to its outer parts, and as a consequence one must solve a spatially non-homogeneous problem. But it suffices to solve a simpler problem.

Let us suppose that field lines stretch from the injection region to the outer parts of the cauldron and that injected particles in one element and their descendants move along these lines and do not interact with those in another element. In this case we can introduce a reference frame co-moving with the injected particles of an element and calculate the evolution of this system of particles with time from the initial stage of injection upto the time of reaching the boundary of the cauldron where the radiation escapes. In our first version of the calculation (Novikov and Stern, 1985), to simplify the problem, we had further assumed that the momentum distribution of particles in the comoving frame is isotropic at all times. But that it is not true was emphasized by Petrosian (in the discussion of Novikov and Stern, 1985). In our present calculations we do take into account that charged particles rapidly lose energy when the pitch angles are large. The momentum distribution of particles then becomes anisotropic. (The process of isotropization may be possible.) It turns out that even if we take the anisotropization into account, the results change only slightly.

Under the above simplifying assumptions the problem can be solved numerically with the Monte-Carlo method. It is natural to define the age t of the $e^{\pm}$ soup as the number of collisions of a particle with others until a given moment. The definition depends on the energy of the particle, but we can take a typical particle with energy $m_e c^2$ and with the classical Compton cross-section $\sigma_0 = 2\ 10^{-25}\ \mathrm{cm}^2$.

We shall characterize the optical depth τ of the whole cauldron by the age t at the moment of escape. This parameter in fact is the dimensionless measure of the cauldron compactness. Indeed

$$\tau = \frac{L}{R}\,\frac{\sigma}{4\ m_e c^3} \approx (L/R)/(10^{30}\mathrm{erg\ s^{-1} cm^{-1}})$$

Thus, the results of the calculations for different moments of time t may be treated as the results for $e^{\pm}$ cauldrons with different values of the compactness L/R.

The parameters of $e^{\pm}$ cauldron are:

1) The magnetic field H, and (2) the primary energy of injected particles E_o. It is the upper bound $\varepsilon_m = (H/H_o)\,E_o^2$ (where $H_o = 4\ 10^{13}$ Gs) of the synchrotron spectrum from primary pairs rather than the primary energy E_o that is important in the problem and we use it as a parameter. (3) the ratio Ω of the energy density of injected particles to the energy density of the magnetic field H. This parameter describes the relative value of Compton processes with respect to synchrotron emission, and (4) the optical depth τ of the whole cauldron.

The outcome of these processes are different for different cases, $\varepsilon_m >> 1$, $\varepsilon_m \approx 1$ and $\varepsilon_m < 1$ for the following reasons. If $\varepsilon_m >> 1$ then a cascade degradation of energy occurs because the descendant synchrotron photons are energetic enough to produce pairs. If $\varepsilon_m \approx 1$ then the energy does not degrade in the cascade way. All pairs are produced by the radiation from the primary particles. In the case $\varepsilon_m < 1$, synchrotron photons are too soft and cannot produce pairs, but the pair production goes through comptonized photons if Ω is not small.

Figures 1-5 demonstrate the results of our new calculations.

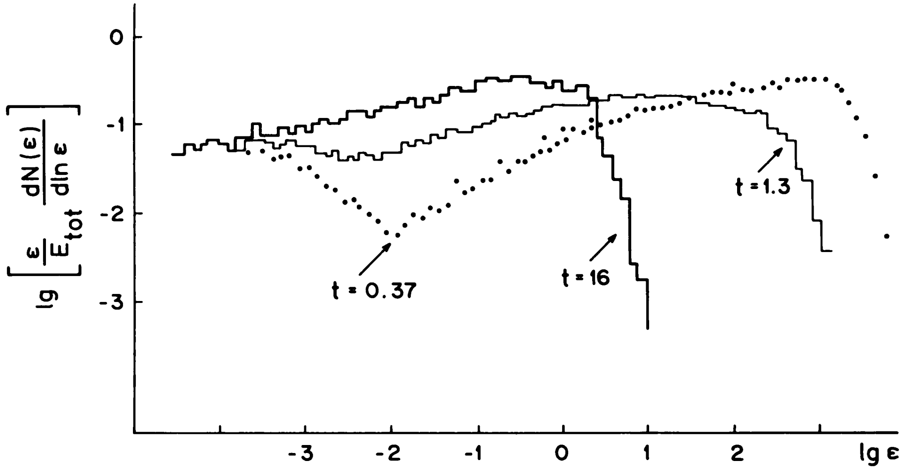

Fig. 1: The evolution of the photon energy distribution with age.
$H = 10^3$ Gs, $E_0 = 10^7$, $\varepsilon_m = 3\ 10^3$, $\Omega = 5$.

Figure 1 demonstrates the evolution of the photon spectrum with age. Note that the photon spectra are presented in figures with the scale $\frac{\varepsilon}{E_{tot}} \frac{dN(\varepsilon)}{d\ell n\varepsilon}$ which is useful for theoretical consideration, but inconvenient for presenting the observational data. In the latter case, one uses the scale with the spectral luminosity $L_\varepsilon = dL/d\varepsilon$. In case of a power-law spectrum, $L_\varepsilon \sim \varepsilon^{-\alpha}$, and our spectral index is then $\beta = 1 - \alpha$. Figure 1 corresponds to the case when Ω is of the order of unity, which means that there is an equipartition in energy between particles and the magnetic field. The parameter $\varepsilon_m = 3\ 10^3$ which is $>>1$.

At small t ($t << 0.37$) there is a typical synchrotron spectrum of a e^- or e^+ decelerating due to its radiation and $\alpha \approx 0.5$ or $\beta = 0.5$. At $t = 0.37$, the intensity rises for $\varepsilon < 10^{-2}$ due to the synchrotron radiation of the next generation of pairs. For $t > 1$ the minimum is smeared out due to componization of synchrotron photons and for $t >> 1$, the spectrum becomes flatter.

The hard part of the spectrum has a cut off due to the pair production. This cut off moves to the region of energy ~ 0.5 MeV with age.

The spectral index of the resultant spectrum lies near the value $\alpha \approx 0.75$.

Analogous results are obtained in the case $\varepsilon_m >> 1$ for a wide range of variation of parameters. This can be easily understood. It was already noted by Bonometto and Rees (1971) that if the number n of pair production cascades grew and became much larger than 1, then the spectral index of particle radiation tended to $\alpha = 1$. These authors dealt with particle energy loss due to Compton scattering, but the same arguments are valid in case of synchrotron energy loss.

It can be shown easily (see e.g., Svensson, 1985) that the spectral index of radiation emitted by the cooling particles of each subsequent generation relates to the spectral index of the previous generation in the following way

$$\alpha_{n+1} = \frac{\alpha_n + 1}{2}$$

The spectral index of the radiation of injected particles, $\alpha_0 = 0.5$. The first generation pairs will have $\alpha_1 = 0.75$. If it is the first generation that is responsible for the radiation from the cauldron (after the Compton smearing-out of the minimum) then $\alpha_{observed} = \alpha_1 = 0.75$. It is this case that is realised for a wide range of values of $\varepsilon_m >>1$. That is why the "universal spectrum has the slope $\alpha \approx 0.7$. If later generations are important then $\alpha \to 1$.

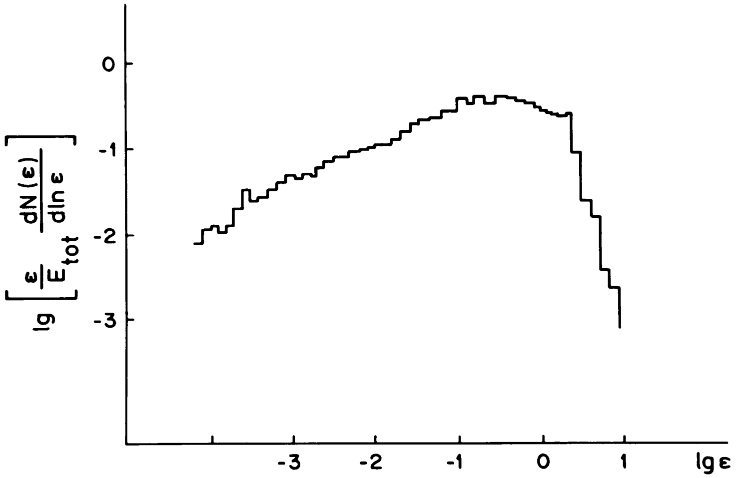

Fig. 2: The final photon energy distribution (t = 16) when the magnetic field is turned off at t = 0.12.

$H = 10^4$ Gs at $t < 0.12$,
$H = 0$ at $t < 0.12$
$E_0 = 10^6$, $\Omega = 5$.

Figure 2 demonstrates another result of our simulation. In this case we try to imitate the inhomogeneity of the magnetic field in the cauldron. For that we turn off the magnetic field at $t = 0.12$. As a result the spectrum becomes steeper because in this case synchrotron radiation is absent after $t = 0.12$ and only some part of the energy is transferred to the soft part of the spectrum.

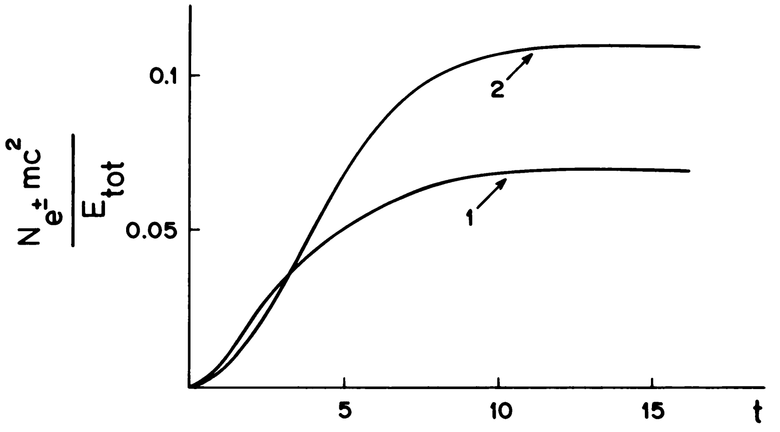

Fig. 3: The yield of pairs versus age.
1. $H = 10^3$ Gs, $E_o = 10$, $\Omega = 5$.
2. $H = 10^4$ Gs at $t < 0.12$; $H = 0$ at $t > 0.12$,
$E_o = 10^6$, $\Omega = 5$.

Figure 3 demonstrates the evolution of the number of pairs with age. The efficiency of $e^{\pm}$ pair rest-mass-energy generation could be equal to 0.1.

The natural question which arises is what the shape of the final spectrum would be in case there is no magnetic field in the region. (This question was raised by M. Rees at the discussion of our previous paper, Novikov and Stern, 1985.) We have done a numerical simulation for this case. The results of our simulation are presented in Figures 4 and 5. Obviously, in this case, we need some soft photon targets for injected particles. But it should be noted that in our simulation the energy in the form of soft photons is only a small part of the total energy, $E_{soft} = 5\ 10^{-3}\ E_{tot}$. In case $E_{soft} \sim E_{tot}$ the final photon spectrum should be flatter. However, we feel that the $e^{\pm}$ cauldron model with the magnetic field seems more realistic. This model can explain the main features of the hard radiation from AGN and quasars. Thus an electron-positron cauldron may be a widespread phenomenon in the universe.

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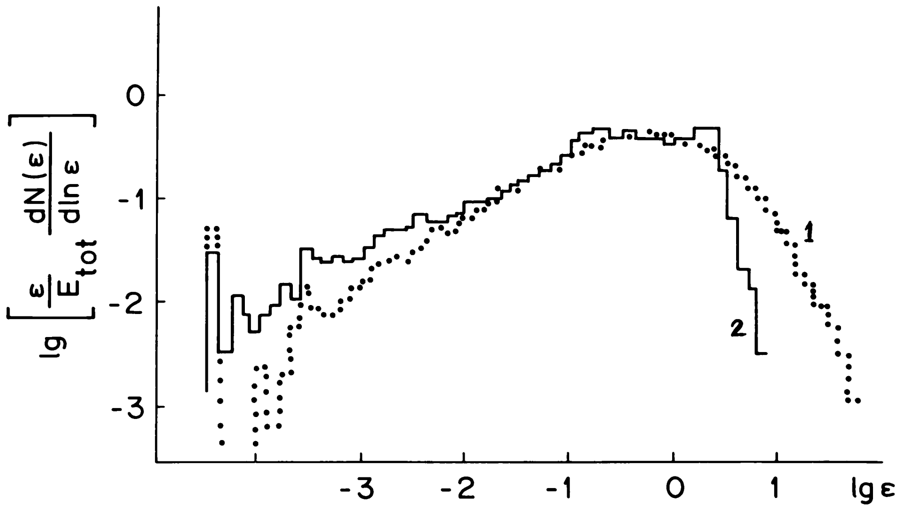

Fig. 4: The final photon energy distribution (t = 18) for the cauldron without the magnetic field, $E_{soft} = 5.10^{-3} E_{tot}$

1 - $E_o = 2.7 \ 10^4$, $\varepsilon_{soft} = 2.7 \ 10^{-5}$

2 - $E_o = 470$, $\varepsilon_{soft} = 2.7 \ 10^{-5}$

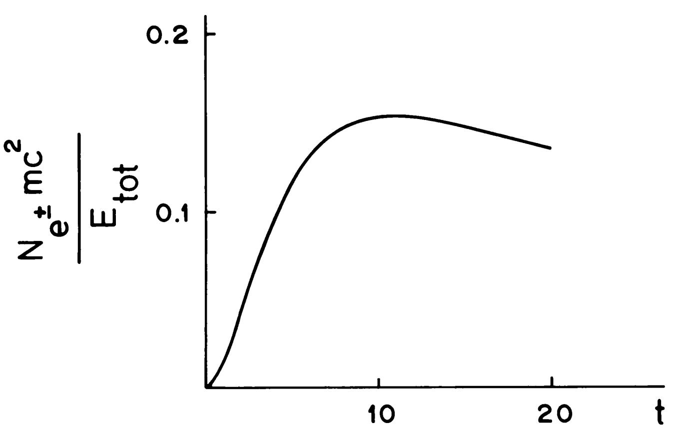

Fig. 5: The yield of pairs versus age $H = 0$, $E_o = 470$, $E_{soft} = 2.7 \ 10^{-5}$, $E_{soft} = 5.10^{-3} E_{tot}$.

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DISCUSSION

Svensson : Besides the Monte Carlo calculations by Dr.Novikov et. al. it has also been possible to solve certain cases of nonthermal pair cascades analytically. Many of the properties of such cascades are then explained easily. (See review in IAU Coll.Nr.89, Radiation Hydrodynamics, and references therein.)

Novikov : I want to say in the review of Dr.Svensson many problems are solved analytically, and it is very important. But only numerical modelling of the processes can demonstrate their evolution with time and clear up the important details.

Wandel : In your model a single generation gives a spectral index of 0.75, appropriate for Seyferts, while for more than one generation the spectral index quickly converges to unity, which is more appropriate for optical quasars. Can the model account for the apparent difference between Seyferts and optical quasars ?

Novikov : Yes it can. The slope of the spectrum depends on the parameters of the $e^{\pm}$ Cauldron, first of all on the initial ε_m. In the case $\varepsilon_m < 1$ the slope is $\alpha \sim 0.5$. If $\varepsilon_m >> 1$ the slope is $\alpha \sim 0.75 \div 1$. So it is a test for the energy of the injected particles. In the case of quasars some additional mechanism of the formation of hard spectrum may be important also. For example, it could be the mechanism of the γ-beam model (see Kardashev et.al., 1983).

Rees : The slope of the X-ray continuum spectrum is influenced not only by the secondary relativistic pairs produced in the cascade, but also by Comptonisation due to the optically thick subrelativistic (quasi-thermal) pairs.

Blandford : I would comment that our (Fabian et.al. 1986) preliminary results indicate that steeper ($\alpha \sim 1$) X-ray spectra are produced when the compactness parameter is increased. This may be relevant to interpreting the optical quasars analysed by Dr.Elvis. However, before we rush to this sort of interpretation, we must convince ourselves that the three approaches (analytic, Monte Carlo and Kinetic) give consistent and robust results.

Segal : You and others are modelling the dynamics of a large-scale many-particle system in terms of 2- or 3-particle processes. Might it not be more natural to use a fluctuation in a statistical state of a QED field ? In particular, could a random fluctuation in the CBR be significantly involved in starting the process you describe ?

Novikov : May be, I do not know. But it is another problem.

Burbidge : Your unified scheme for the whole nonthermal spectrum is quite attractive. Can you relate it to the observations since presumably different parts of the spectrum arise in different sized volumes ?

Novikov : We have considered mainly the hard part of the continuum, but it is quite possible that the soft part of the continuum has the same origin. The Cauldron can operate if τ is great enough. For quasars it means that R is less than $\sim 10^{15}$ cm. The line spectrum arises on the larger scales.

Rees : One general statement, however might be that the pair plasma is restricted to length scales below $\sim 10^{17}$ cm (for quasar luminosities). It's important that the optically thick cloud of thermal pairs can have effects on the optical continuum as well as on X-rays - for instance, high synchrotron-type polarization would be destroyed. One interesting possible test, pointed out by Fabian and collaborators, is that the X-ray variability should display rises in hard X-ray flux that are stronger than the falls.

Canizares : Many compact galactic X-ray sources have "compactness" parameters, $\tau >> 10^{30}$. Should not these processes then be more evident and detectable in these galactic sources than in AGN ?

Novikov : Probably only pulsars with appropriate parameters and accreting black holes can produce a large acceleration power in a small volume to give rise to an electron-positron Cauldron. May be some of the galactic X-ray sources can be an $e^+ e^-$-Cauldron.

Rees : White et. al., and other authors, have attributed the transition between two well-defined states in (for instance) Cygnus X1 - a high luminosity state with soft spectrum, and a lower luminosity state with harder spectrum - to the presence and absence, respectively, of an optically thick pair plasma.

Burke : Imaging studies on the scale suggested by your "Cauldron" calculations would be useful for verification. The necessary resolution scale could be reached by aperture-synthesis imaging at optical wavelengths. No such instruments are in prospect at the moment, but could be built if the programs can be started.

Rees : Perhaps gravitational lensing can do it, as suggested by Canizares and others ? That is the poor man's method, anyway.

Burke : One method depends on luck, the other on planning.

Dultzin-Hacyan : The cloud with which the central beam interacts (in the model of Kardashev et.al. (1983)) has very specific physical conditions (T and P). To what extent does the predicted observed radiation depend on these physical conditions of the cloud ?

Novikov : The physical parameters of the cloud in our γ-beam model could be considered as physically reasonable in the case when a gas-cloud target is a result of a disruption of a star by the tidal forces of a black hole or as a result of a collision with another normal star. We predict the strong variations of the continuum in the range 300-500 keV due to variations of thermal photon density in the cloud. Variability of the continuum and the annihilation line are the result of the motion of the cloud and the change of irradiation condition of the cloud by the directed beam.