

AMES GRANT  
IN-CR  
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FINAL REPORT

on

NASA-Ames Cooperative Agreement NCC 2-364

EVOLUTION OF PHOTON AND PARTICLE SPECTRA IN COMPACT, LUMINOUS OBJECTS

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*Period covered:*

August, 1985 - September, 1988

(NASA-TM-101247) EVOLUTION OF PHOTON AND  
PARTICLE SPECTRA IN COMPACT, LUMINOUS  
OBJECTS Final Report, Aug. 1985 - Sep. 1988  
(NASA) 11 F CSCL 20H

N89-14825

Unclas  
G3/72 0174663

The overall intent of this work was to investigate the physics of high energy photons and particles (especially electrons and positrons) in the compact, high-energy-density environment of active galactic nuclei and quasars ("AGN"). These objects are observed to contain hard X-ray and  $\gamma$ -ray (with  $h\nu \gtrsim m = ec^2$ ) photons and relativistic electrons and/or positrons (with  $E \gg m_{ec^2}$ ). The high energy density, and consequent high optical depth, of the nuclear region means these particles are very likely to interact with each other as well as with their surroundings before emerging from the nucleus and being observed.

The fundamental goal of the work was to determine the effect of this compact, optically thick "atmosphere" on the emergent particle and photon spectra. This was pursued by developing and applying a numerical code which follows the nonlinear spectral evolution of a pair/photon plasma, due to two-body scattering and interaction processes, in an unmagnetized system. The code was applied both to static plasmas and to relativistic, expanding winds. The first application, while not physically correct for long times (when other processes, not included in the code, must come into play), explored the fundamental effects of the microphysics on the spectral evolution. The second application is probably the relevant one for active galactic nuclei: the expansion of an internally relativistic plasma will at some point shut off ("freeze out") the reactions and determine what an external observer sees.

Several related tasks were performed during the grant period:

- a) developing a formalism to account for the effect of mass creation and annihilation on a relativistic wind;
- b) modelling coherent radio emission from relativistic electron beams in active galactic nuclei;
- c) writing and presenting an invited review on the role of high energy pairs and

photons in active galactic nuclei, at the "Supermassive Black Hole" meeting held to George Mason University, October, 1986.

This work is summarized in this Final Report.

### Code Development and Cross Sections

The overall picture assumed in the calculation is that of an optically thick, isotropic pair/photon fireball, with no escape of pairs of photons, nor any radiative transfer. This might, for instance, represent the optically thick atmosphere of the hot inner regions of a thin accretion disk, or the nonlinear development of an electrodynamic pair/photon cascade in a nuclear Poynting flux beam.

The evolution of the pair or photon spectrum -  $n_\alpha(E)$  - due to two-body processes is given by

$$\frac{dn_\alpha(E)}{dt} = \sum_{\beta,\delta} \int n_\beta(E') n_\delta(E'') v_{\beta,\delta} \sigma_{\beta,\delta}(E', E'') g_{\beta,\delta}(E', E''; E) dE' dE'' \quad (1)$$

where  $\sigma_{\beta,\delta}$  is the total cross section for species  $\beta$  and  $\delta$  at energies  $E'$  and  $E''$ ;  $v_{\beta,\delta}$  is the relative velocity of the two quanta; and  $g_{\beta,\delta}$  is the distribution of output energy  $E$  from this reaction. The indices  $\alpha, \beta$  and  $\delta$  take the values  $e$  (for pairs) or  $\gamma$  (for photons). Equation (1) was solved numerically by discretizing energy space in logarithmic bins, so that the number in bin  $i$  is

$$n_{\alpha i} = \int_{bin\ i} n_\alpha(E) dE \quad (2)$$

and the reaction rate coefficient is

$$c_{\beta j, \delta k}^{\alpha i} = \frac{1}{c\sigma_T} \int_{bin\ i} f(E) v_{\beta j, \delta k} \sigma_{\beta,\delta}(E_j, E_k) g_{\beta,\delta}(E_j, E_k; E) dE \quad (3)$$

The distribution within the bin,  $f(E)$ , was assumed to be  $f(E) \propto 1/E$ . If equation (1) is normalized to some fiducial density,  $n_o$ , and to a characteristic collision time, using  $\tau = c\sigma_T n_o t$ , the discretized equation becomes

$$\frac{dn_{\alpha i}}{d\tau} = \sum_{\beta,\delta} \sum_{j,k} n_{\beta j} n_{\delta k} c_{\beta j, \delta k}^{\alpha i} \quad (4)$$

The equations represented by (4) were solved simultaneously, numerically, to get the spectral evolution,  $n_{\alpha i}(\tau)$ , for  $\alpha = e, \gamma$  and for each  $i$ .

The differential cross sections,  $c_{\beta j, \delta k}^{\alpha i}$ , necessary for this calculation were evaluated for four two-body reactions: pair annihilation, two-photon pair creation, Compton scattering, and electron-electron bremsstrahlung; these are the most important reactions at moderate energies ( $\sim$  MeV to GeV) in unmagnetized plasmas. Calculating  $c_{\beta j, \delta k}^{\alpha i}$  required integrating the full, differential cross sections – which are available in the literature – over scattering angles (in the center of momentum or electron rest frames) and energies consistent with bin  $i$ . This was done numerically by Monte Carlo methods. The energy space bins ran from  $3 \times 10^{-3} m_e c^2$  to  $30 m_e c^2$ , in steps of  $\Delta \log(E/m_e c^2) = 0.5$ . Imposed "rebinning" of the output of the Monte Carlo code ensured energy and number conservation to very good accuracy at each step.

## 2. Evolution of Non-Expanding systems.

This code was developed to model expanding fireballs, as in active nuclei – where the conditions are such that the two-body processes listed above will be important, but where expansion of the fireball will freeze out the spectrum before other processes (such as three-body processes, free-free absorption, etc) have had time to occur. We began, however, by using the code to follow the evolution of a confined, constant-density pair/photon plasma under the four processes listed above. This allowed the effect of the reactions to be studied in isolation, separate from the effects of the fireball expansion. Clearly, this code cannot follow the evolution of a closed system toward true thermal equilibrium, as inverse and three-body processes are not included. This study will, however, provide a good description of the early phases of thermalization, when the two-body processes included are the most important ones, and thus will allow intelligent interpretation of the results of the expanding-wind calculations.

The numerical runs started with an arbitrary initial pair and/or photon spectrum – the "creation" spectrum. This might, for instance, be envisioned to be the

pair/photon spectrum produced by a hot, inner accretion disk around a massive black hole; or particle pickup and acceleration in a Poynting flux beam. Four types of "creation" spectra were chosen – monoenergetic pair and photon spectra, and "white" pair and photon spectra (in which  $n(E) \propto E^{-2}$ , giving a flat energy spectrum). About fifteen different "creation" spectra at various energies within these categories were followed to long times.

It was found that each experiment evolved as follows. The early phases of the evolution consisted of a slow evolution away from the initial spectrum, toward a common, "quasi-equilibrium" spectrum. This spectrum is maintained by non-local (in energy space) scattering and energy transfer processes; thus it reflects the two-body differential cross sections rather than the initial conditions. Both pairs and photons share this common shape at most energies; the pair/photon ratio reflects the creation/annihilation rate balance. This common spectral shape was reached initially at moderate ( $\sim m_e c^2$ ) energies. On a longer timescale, higher and lower energies reached this common spectrum. In particular, initial high-energy ( $\gg m_e c^2$ ) quanta were eventually degraded by interactions with cooler quanta; low-energy quanta were created by bremsstrahlung and by scattering. Two unexpected and important trends appeared in these experiments.

The first interesting result concerns the rate at which the system reaches this mid-energy "thermal" peak. This rate might, naively, be expected to be controlled by the dominant reaction likely in the creation spectrum – two-photon pair creation in a photon spectrum, and pair annihilation in a pair spectrum. Indeed, such "linear" estimates have been commonly used in the literature. However, the strongly non-linear nature of the system does not bear out this approach. Monoenergetic starts were found to evolve much faster than the linear estimates would predict (by a factor  $\sim 10^2$ , typically; the exact rate depended on the specific creation spectrum). White starts were found to evolve much more slowly than the linear estimate (again by a factor  $\gtrsim 10^2$ ).

The second interesting result is the emergence of the slowly evolving, quasi-equilibrium spectrum. This spectrum appears on timescales that should just be reached in the most compact AGN, before the wind expansion shuts off the evolution. This quasi-equilibrium spectrum has a broad peak, centered initially at  $\bar{E} \sim 0.1m_e c^2$ , in both  $n_e(E)$  and  $n_\gamma(E)$ . This peak decays only slowly to higher energies, being reduced by  $\sim 10^3$  at  $\sim 30\bar{E}$  for instance. The spectrum at the highest initial energies slowly degrades from its initial state to an approximate exponential tail. The low-energy side of the broad peak has  $n(E) \propto E^{1/2}$  for both pairs and photons; for pairs this continues to the lowest energy in the calculation, while for photons the spectrum at the lowest energies is approximately flat, reflecting the creation of soft photons by bremsstrahlung. The form  $n(E) \propto E^{1/2}$  is the low-energy limit of the Maxwell-Boltzmann distribution. This quasi-equilibrium evolves slowly, at a rate determined by the rate of bremsstrahlung creation of photons by pairs at the mean energy,  $\bar{E}$ . As this process continues,  $\bar{E}$  decays and the photon creation rate slows down even further. While the average energy decays, both the pair and photon spectra keep their characteristic shape, but the ratio  $n_e(E)/n_\gamma(E)$  decays as fewer photons exist with energies above the pair creation threshold.

None of the runs was followed much beyond this point, both because other processes not included in the code would become important, and because the long-term evolution is probably not important in AGN.

### 3. Incorporating the Relativistic Wind

In the AGN environment, a relativistic pair/photon plasma with  $\bar{E} > GMm_e/r$  (and with  $GMm_e/r \lesssim m_e c^2$ ) is unlikely to remain trapped; rather a relativistic expansion is likely. Such an expansion will modify the spectral evolution described above by "freezing out" the reactions at some intermediate point. The emergent spectrum will probably not be the fully thermalized, quasi-equilibrium described above, but rather some intermediate shape reflecting the effective optical depth of the flow and, for "thin

flows", the creation spectrum.

In order to include these effects in the models, one must know the velocity field of the wind,  $v(r) = c\beta(r)$  (assuming a steady flow), or the bulk Lorentz factor,  $\gamma(r) = (1 - \beta(r)^2)^{-1/2}$ . When the internal energy of the fluid is well above the gravitational potential, the flow is determined by

$$w \frac{d\gamma}{dr} = -\gamma \frac{dp}{dr}. \quad (5)$$

where  $w = \frac{\Gamma}{\Gamma+1}p + \rho c^2$  is the enthalpy of the fluid;  $\rho$  is the density and  $p$  is the pressure of the fluid;  $\Gamma = d \ln p / d \ln \rho$  is the adiabatic exponent. If mass were conserved, this equation could be reduced to one in only  $\gamma(r)$  by adding a continuity equation and an equation of state (usually assumed to be adiabatic,  $p/\rho^\Gamma = \text{constant}$ ). However, pair creation and annihilation means the adiabatic exponent is a complicated function of local conditions, and cannot easily be incorporated into (5).

Instead,  $dp/dr$  was evaluated explicitly at each step. This was done by noting that, in terms of the binned  $n_i$ ,

$$p = \frac{1}{3} m_e c^2 \sum_i \left[ n_{ei} \left( \epsilon_i - \frac{1}{\epsilon_i} \right) + n_{\gamma i} \epsilon_i \right] \quad (6)$$

(noting that  $E_i = \epsilon_i m_e c^2$  is the total, not kinetic, energy of the  $i$ th bin). The pressure gradient in (5) can then be evaluated explicitly by chain rule, with a pseudo-continuity equation invoked to account for the rate of change of specific volume in the flow. This leads to

$$\frac{dp}{dr} = -\frac{1}{3} \left( \frac{2}{r} + \frac{\gamma}{\gamma^2 - 1} \frac{d\gamma}{dr} \right) A(r) + R(r) \quad (7)$$

where

$$A(r) = \frac{1}{3} m_e c^2 \sum_i n_{ei} \left( \epsilon_i - \frac{1}{\epsilon_i} \right) \left( \frac{4}{3} + \frac{1}{3} \epsilon_i^2 \right) + \frac{4}{9} m_e c^2 \sum_i n_{\gamma i} \epsilon_i$$

and

$$R(r) = \frac{1}{3} m_e c^2 \sum_i \left[ \frac{dn_{ei}}{dr} \left( \epsilon_i - \frac{1}{\epsilon_i} \right) + \frac{dn_{\gamma i}}{dr} \epsilon_i \right]$$

and  $dn_{ei}/dr$  and  $dn_{\gamma i}/dr$  are the rates of change due to the two-body reactions; *c.f.* equation (4), and equation (9), below.

Combination of (7) with (5) allows explicit evaluation of  $\gamma(r)$  within the calculation.

#### 4. Spectral Evolution in an Expanding Wind

The case of an expanding wind was modelled by following the evolution of the flux at radius  $r$ ,

$$f = 4\pi r^2 n \beta c / F_o \quad (8)$$

(normalized to some constant flux,  $F_o$ ). The number density in (8) is that in the observers frame; in the co-moving (fluid) frame,  $n^f = n/\gamma$ . The binned rate equation, analogous to (4), becomes

$$\frac{df_{\alpha i}}{dx} = \frac{\eta}{\gamma^2 \beta^2 x^2} \sum_{\beta, \delta} \sum_{j, k} f_{\beta j} f_{\delta k} c_{\beta j, \delta k}^{\alpha i} \quad (9)$$

where  $x = r/r_o$  ( $r_o$  is a scaling radius). The parameter

$$\eta = \frac{F_o \sigma_T}{4\pi r_o c} \quad (10)$$

scales the effective optical depth of the flow (and is also related to the compactness, usually defined in terms of the luminosity,  $L$ , as  $L/r_o = F_o \bar{E}/r_o$ ).

The experiments run for the non-expanding case, section 2 above, were repeated for the expanding case. Equations (9) for the spectrum were solved simultaneously with (5) and (7) for the flow. It was found that the geometry of the flow fairly quickly approached the usual adiabatic, mass conserving solution to (5) – namely,  $\gamma(r) \propto \gamma(r_o)r/r_o$ , for systems with only a moderate amount of pair creation/annihilation. It

was also found that emergent (frozen out) spectrum is predicted, given the creation spectrum, by the optical depth

$$\tau(x_o) = \eta \int_{x_o}^{\infty} \frac{dx}{\gamma^2 \beta^2 x^2} \quad (11)$$

This is the quantity which measures the "number of collision times", and can be directly compared to  $\tau = t/t_o = c\sigma_T n_o t$  in the non-expanding runs. The emergent spectrum in a given case, that is for particular values of  $\eta$ ,  $\gamma_o = \gamma(x_o)$  and a particular creation spectrum, can be determined from the static solutions by choosing the scaled parameter,  $\tau$ , equal to  $\tau(x_o)$ . For flows which are close to the adiabatic solution, (11) shows that  $\tau(x_o) \simeq \eta/\gamma_o^3$  (since  $x_o = 1$  in general), so that the flow speed as well as the compactness determine the effective optical depth of the wind.

## 5. Impact on the Surroundings and How the Flow is Observed

The spectral evolution calculations were carried out in the co-moving (fluid) frame. The particle and photon spectra seen by an external observer will be Doppler shifted to higher energies. If the flow velocity at freeze-out,  $\gamma_{last}$ , is highly relativistic, then each quantum will be shifted up in energy by  $E \simeq \gamma_{last} E^f$ , if  $E^f$  is that quantum's energy in the fluid frame.

The blueshifted photons, at least those with energies  $\gtrsim$  several keV, are likely to be observed directly. This calculation is thus roughly consistent with the observed hard X-ray/ $\gamma$ -ray peak seen around  $h\nu \simeq m_e c^2$  seen in AGN.

The energetic pairs will not be seen directly. They can impact and interact with the local interstellar medium. For instance, they can act as the transrelativistic seed particles necessary for shock or turbulent Fermi acceleration to highly relativistic energies. The particles can be seen indirectly through their radiation. Escaping positrons will of course annihilate on the local ISM; their high energies will result in a broad emissivity, centered  $\sim 1$  - several MeV probably. Both species can produce synchrotron radiation, which would be expected to appear at radio to optical frequencies.

One might ask how synchrotron radiation can be appended to a calculation which was done for an unmagnetized plasma. The effect of a magnetic field would be to add synchrotron losses to the basic processes determining the spectral evolution, and to affect the flow dynamics. It was found that the first effect is unimportant for fields which satisfy

$$B^2 \ll \frac{m_e^2 c^3}{e^4} \frac{L}{4\pi r^2} \frac{\sigma_e}{\epsilon_e \epsilon_\gamma} \simeq \frac{m_e^3 c^6}{e^4} \frac{\sigma_e}{\sigma_T r_0 \epsilon_e} \eta \quad (12)$$

if  $\sigma_e$  is the cross section of the dominant reaction for the pairs,  $\epsilon_e$  is the normalized mean energy of the pairs and equation (10) has been used. The magnetic fields are not important in the flow dynamics if

$$B^2 \ll \frac{2L}{r^2 c} \simeq 8\pi \frac{m_e c^2 \bar{\epsilon} \eta}{\sigma_T r} \quad (13)$$

where  $\bar{\epsilon}$  is the mean (pair and photon) energy. For "conventional" bright quasar numbers, both (12) and (13) say that magnetic fields must be stronger than several hundred Gauss to have a strong effect on the evolution of the fireball. Fields weaker than this can still lead to detectable synchrotron emission without vitiating the unmagnetized calculation.

Another possibly interesting effect of these escaping electrons was explored by the P.I. in collaboration with D. Baker (LANL/NASA), J. Borovsky (LANL) and G. Benford (U.C. Irvine). In this work, which was separate from the numerical calculation above, it was noted that relativistic electrons might well be beamed, rather than isotropic, when they first encounter the nuclear (or jet) plasma in AGN. If this is the case, rapidly-growing electrostatic turbulence (such as Langmuir turbulence, from a streaming instability) can give rise to strong collective emission of electromagnetic waves. This phenomenon is observed in the lab, where it is found that this emission can mimic the nonthermal, polarized emission usually interpreted as incoherent synchrotron. It was found that longer-wavelength electromagnetic instabilities could distort an initially ordered magnetic field and twist the collective emission into the observer's line of sight. Thus, it was argued that some part of the nuclear radio emission

observed from AGN might be due to collective processes rather than (or in addition to) incoherent synchrotron emission.

Finally, an invited review was written on the role of high-energy particles and photons in the environment of massive black holes (which are thought to be the energy source for AGN). Observations of high-energy quanta were reviewed, and general theoretical considerations as to the physics of these energetic quanta (both their initial "creation" in nuclear accretion flows, and their "post-processing" according to the work described in this Final Report) were presented.

## 6. Bibliography

### *Published Work Arising from This Project*

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### *Work in Preparation Arising from This Project*

Eilek, J. A., Caroff, L. J., Noerdlinger, P. D. and Dove, M. E., *Spectral Evolution of an Unmagnetized Pair-Photon Plasma*, to be submitted to *Ap. J.*

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