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LBL-35120
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V. Krishan

January 1994

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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Stimulated Cerenkov-Radiation Processes in Dusty AGN*

Vinod Krishan*
Indian Institute of Astrophysics
Bangalore—560 034, India

Abstract— An electron moving with a superluminal velocity in a dielectric medium gives rise to spontaneous Cerenkov radiation. If, instead of a single electron, a high density superluminal electron beam is made to pass through a dielectric, the spontaneously generated radiation will grow exponential with distance and is known as stimulated Cerenkov-Compton radiation. If, in addition, an incident electromagnetic field interacts with a strong superluminal or subluminal electron beam, a frequency up-converted stimulated scattered radiation is produced, which by analogy to a similar process in vacuum with subluminal electron beams, is known as Cerenkov-Raman radiation. We explore and point out the role of these processes in the dust environs of Active Galactic Nuclei (AGN). Since, the refractive index of the dust matter is a key factor in these processes, their inclusion links the properties of the dust grains with the characteristics of the non-thermal continuum especially in the infrared range, which, the observations show to be particularly bumpy and therefore requires additional contributions over the thermal continuum.

Subject Heading: Active Galactic Nuclei, Dust, Radiation Processes Cerenkov, Nonthermal Continuum.

*Visiting Lawrence Berkeley Laboratory Oct.14, 1993 - January 16, 1994.

Work supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract NO. DE-AC03-76SF00098.

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1. Introduction

Dust, in the universe, is best known for its reddening and polarization properties. It absorbs ultraviolet radiation, becomes hot and radiates the thermal spectrum corresponding to its temperature. The highest temperature, it can attain before sputtering is ~ 2000 K. which gives, from the Wien's displacement law, a maximum wavelength $\lambda_m \approx 1.5 \mu\text{m}$. Evidence for the presence of dust in AGN comes from the strong thermal infrared, the $3.3 \mu\text{m}$ emission, the $10 \mu\text{m}$ silicate absorption and polarization of the continuum and the lines. The composition of the dust in AGN is suspected to be different from that of circumstellar and interstellar dust. This is inferred from the near absence or weakness of the $2200 \text{ \AA}$ absorption feature, though this is also true for the stars seen in the Magellanic clouds. A dust to gas ratio of ~ 10 percent of the galactic interstellar medium has been inferred from a comparison of resonance and non-resonance lines. A disk-like or a torodial distribution with 10-20 times the dimensions of the flattened broad line emitting region has been invoked to explain the asymmetric line profiles and reddening. The dust particle sizes have been deduced to be much smaller than the sizes of the interstellar grains (MacAlpine 1985; Rieke 1985; Lawrence 1987; Kailey and Lebofsky, 1987).

To the best of our knowledge, the interaction of high energy electrons, which are routinely summoned for synchrotron, inverse Compton, stimulated Compton and Raman scattering processes, with dust in AGN, has not been investigated, perhaps for two reasons. First, the spontaneous Cerenkov emission is a rather weak process and second it is hard to drive electron beams, unless they are of extremely high energy, through a dielectric medium. In this paper, we shall show that the exponentiation rates of stimulated Cerenkov processes are comparable to the rates of the analogous processes occurring in a plasma (Hasegawa 1978, Krishan 1993 and references therein). Further, for the same electron velocity, the frequency of the radiation produced by the Cerenkov-Raman process is higher than that produced by the Compton and Raman Processes in a vacuum. With these two attractive features, we explore the role of the Cerenkov processes in AGN environs, without discussing in detail the geometrical distribution of the dust, save to assume that the dust medium is dense enough to have a refractive index.

2. Stimulated Cerenkov Emission

The spontaneous Cerenkov emission, being proportional to the number of electrons, is a weak process. It can be strengthened if a prebunched electron beam of bunch size smaller than the wavelength of the radiation is sent through the medium. The stimulated processes achieve bunching of electrons through the excitation of space charge waves. Thus, a high density electron beam can cause exponential amplification of the spontaneously created radiation. A monoenergetic electron beam of density N_b , and velocity $v_b = \bar{\beta}_o C$ supports a space-charge wave $(\omega, \bar{K})$ such that (Walsh 1980)

$$\omega = \bar{K} \cdot \bar{\beta}_o C \frac{\omega_b}{(\gamma_o + \beta_o^2 \gamma_o^3)^{1/2}} \quad (1)$$

$$\text{where, } \omega_b = \left(\frac{4\pi N_b e^2}{m} \right)^{1/2} \text{ and } \gamma_o = (1 - \beta_o^2)^{-1/2}$$

A beam can be treated as hot or cold if its velocity spread ΔV_b is larger or smaller than ΔV , where, ΔV is the difference between the phase velocity $v_b = (\omega / K)$ of the space-charge wave and the beam velocity v_b . A critical wavevector, K_c can be defined such that the electron beam is hot for $K > K_c$ and cold for $K < K_c$, where K_c is determined from $\Delta V_b = \Delta V$ and is given by

$$K_c = \frac{\omega_b}{(\Delta V_b)(\gamma_o + \beta_o^2 \gamma_o^3)^{1/2}} \quad (2)$$

The details of the calculation of the dispersion relation for the Cerenkov radiation are given in Walsh (1980), from where we reproduce the dispersion relation in the cold beam limit as:

$$(\omega - \bar{K} \cdot \bar{\beta}_o C)^3 - \frac{\omega_b^2 (\bar{K} \cdot \bar{\beta}_o C) \left(1 - \frac{1}{\beta_o^2 \epsilon} \right)}{2(\gamma_o + \beta_o^2 \gamma_o^3)^{1/2}} = 0 \quad (3)$$

with the difference that eq. (3) has been derived without the assumption $\beta_o \sim 1$ and $\gamma_o \gg 1$. Here, the dust medium of dielectric constant ϵ has been assumed to be isotropic.

The astrophysical dust grains, however, come in all shapes and sizes and their gaseous distribution may be far from being isotropic due to their keplerian and other motions. In this paper, however, since our aim is to point out the radiation mechanism, we will defer the geometrical as well as the magnetic issues. Near $\omega \sim C\vec{K} \cdot \vec{\beta}_o \sim \frac{CK}{\sqrt{\epsilon}}$, the Cerenkov conditions, equation (3) gives for the growth rate ω_I in the cold beam limit:

$$\omega_I = \frac{\sqrt{3}}{2} \left[\frac{\omega_b^2 CK \beta_o \cos \theta_c \sin^2 \theta_c}{2\epsilon (\gamma_o + \beta_o^2 \gamma_o^3)} \right]^{1/3} \quad (4)$$

and the real part of the frequency ω_R as

$$\omega_R = C\vec{K} \cdot \vec{\beta}_o - \frac{\omega_I}{\sqrt{3}} \quad (5)$$

where, θ_c is the Cerenkov angle.

In the warm beam limit, the charge and current densities are calculated using the Vlasov equation and the growth rate ω_I is found to be (Walsh 1980):

$$\omega_I = \frac{\pi}{2} \frac{\omega_b^2}{C\vec{K} \cdot \vec{\beta}_o} \frac{\beta_o^2}{(\gamma_o + \beta_o^2 \gamma_o^3)} \frac{1}{E} \left(\frac{C}{\Delta V_b} \right)^2 \quad (6)$$

At the critical wavevector K_C , $\omega_I \sim \omega_R$, which is reminiscent of the transition from stimulated Raman to compton scattering in vacuum (Hasegawa, 1978), of course, at this point, the condition $\omega_I \ll \omega_R$ breaks down. The saturation of the instability can take place through the trapping of the electrons in the wave electric field, among other processes. For the sake of illustration, we invoke the saturation of the wave field E when the bounce frequency ω_B of the electrons in it becomes comparable to the growth rate i. e. $\omega_B = \left(\frac{eEK}{m} \right)^{1/2} = \omega_I$. This determines the energy density $(E^2 / 4\pi)$ from which one estimates the luminosity of radiation L to be:

$$L = E^2 R^2 C \quad (7)$$

where R is the size of the emission region.

In a dielectric, low frequency radiation can be up-converted to a high frequency (ω_s) radiation through a process known as the Cerenkov-Raman, in analogy with the stimulated Raman scattering in a vacuum or a plasma (Krishan 1993). The change in the frequency of radiation due to its scattering off fast electrons in the presence of a dielectric of refractive index $n(\omega)$ can be determined from kinematic relations of energy and momentum conservation and is given as (Walsh 1980):

$$\begin{aligned} \frac{\omega_s}{\omega_i} &= \frac{1 + \beta_o n(\omega_i) \cos \theta_p}{\beta_o n(\omega_s) \cos \theta_s - 1} & \beta_o n(\omega_s) > 1 \\ &= \frac{1 + \beta_o n(\omega_i) \cos \theta_p}{1 - \beta_o n(\omega_s) \cos \theta_s} & \beta_o n(\omega_s) < 1 \end{aligned} \quad (8)$$

Here, θ_p and θ_s are the incident and scattering angles as shown in Fig. (1). Since $n(\omega_s) > 1$, one can have large amplification for smaller values of β_o as compared to the vacuum case. The dynamics of this process involves three-wave scattering where the incident mode ω_i is scattered off the collective mode of the beam electrons into the scattered radiation ω_s . It can be shown that the phase matching conditions for the three-wave process are identical to the kinematics relations. The growth rate for this process can be calculated by using the standard techniques of the parametric instabilities. Here, we give the result as (Walsh 1980):

$$\omega_I = \gamma_{\perp}^2 \left(\frac{\omega_b \omega_s}{\gamma_o^{3/2}} \right)^{1/2} \frac{\beta_{\perp}}{2} \quad (9)$$

where $\beta_{\perp} = eE_i / m\omega_i c$ is the transverse velocity modulation of the electrons provided by the incident wave and $\gamma_{\perp} = (1 - \beta_{\perp}^2)^{-1/2}$. The luminosity can again be calculated by invoking trapping as the saturation mechanism.

3. Radiation Processes in Dusty AGN.

Although, the composition of the dust in AGN may be different from that of the interstellar medium, nobody doubts the presence of graphites and silicates. For the sake of illustration, we choose typical values of the electron beam and the dust parameters as follows:

the electron beam density $N_b = N_{10} \times 10^{10} \text{ cm}^{-3}$ (Krishan and Wiita, 1990)

the Cerenkov radiation frequency $\omega_s = \omega_{14} \times 10^{14} \text{ sec}^{-1}$

the dielectric constant $\epsilon \sim 3$, (Dravine and Lee, 1984)

In the cold beam limit, for $\beta_o^2 \epsilon > 1$, i.e. for $\beta_o \sim 0.6$.

We estimate the growth rate from equation (4) to be:

$$\omega_I \sim 10^{10} \omega_{14}^{1/3} N_{10}^{1/3} \text{ sec}^{-1}$$

and the luminosity from equation (7):

$$L = 10^{46} \frac{R_{pc}^2 N_{10}^{4/3}}{\omega_{14}^{2/3}} \text{ erg / sec.}$$

which is close to the observed value $\sim 10^{42} \text{ erg/sec}$, for the typical source size $R_{pc} \sim 10^{-2}$ and $N_{10} = \omega_{14} = 1$, with the flux $\int_{\omega} = \frac{L}{\omega}$ varying $\omega^{-5/3}$. Thus, the Cerenkov spectrum is steeper than the average observed spectrum with $\alpha \sim -1$ and may account for the peculiarities in the infrared region, where the data indicates a wide range of values varying from ($\alpha \sim -1$ to $\alpha \sim -6$) of the spectral index (Boksenberg, A., Carswell, R.F. and Oke, J.B., 1976, Ap.J. (letters), 206, L121.)

In the warm beam limit, for a thermal velocity spread $(\Delta V_b / C) \sim 10^{-2}$, we estimate the growth rate from equation (6) to be:

$$\omega_I \sim 10^8 \frac{N_{10}}{\omega_{14}} \text{ sec}^{-1}$$

and the corresponding luminosity:

$$L \sim 2 \times 10^{36} \frac{N_{10}^4 R_{pc}^2}{\omega_{14}^6} \text{ erg / sec.}$$

Thus, as expected, since the growth rate in the warm beam case is lower than that in the cold beam limit, one needs electron beams of higher densities to generate the same luminosity. Due to the spectrum $\int \omega \alpha \omega^{-7}$ this process is more efficient at lower frequencies. Thus for $R_{pc} \sim 10^{-2}$, $N_{10} \sim 10^2$ we find $L \sim 2 \times 10^{40} \text{ erg/sec. at } \omega_{14} = 1$. The lower limit on the frequency of the Cerenkov radiation is set by the condition that the growth rate ω_I should be much less than the real part ω_R since growth rate has been derived under this assumption. This gives $\omega_{14} \gg 10^{-2}$ for the parameters chosen here.

In conclusion, a warm beam of reasonable density and without a thermal spread $\sim 10^{-2}$ can generate enough radiation in the far infrared and the infrared range to contribute to the spectrum of AGN.

We illustrate the Cerenkov-Raman Case, by choosing the wavelength of the incident radiation $\lambda_i \sim 2.09 \mu$, at which the refractive index $n(\lambda_i)$ for graphite ~ 3.56 (Dravine and Lee, 1984). We find from equation (8), the wavelength of the scattered radiation $\lambda_s \sim 0.15 \mu$, $\frac{\omega_s}{\omega_i} = 42$, for $n(\lambda_s) \sim 1.27$, $\theta_p = \theta_o \sim 0$, $\beta_o \sim 0.8$ and $\gamma_o^2 \sim 3$.

The frequency of the Raman scattered radiation in vacuum or a plasma is given by $\omega_s \sim 4\gamma_o^2 \omega_i = 12\omega_i$. Thus, the Cerenkov-Raman process results in a larger frequency upshift than the Raman process in a vacuum or a plasma for the same electron beam energy. From equation (9) the growth rate for the Cerenkov-Raman process is estimated to be:

$$\omega_I \sim \beta_{\perp} \times 0.16 \times 10^{12} N_{10}^{1/4} \omega_{14}^{1/2} \text{ sec}^{-1}$$

for $\gamma_{\perp} \sim 1$ and $\gamma_o^2 = 3$, and the luminosity $L = 0.5 \times 10^{45} \beta_{\perp}^4 N_{10} \text{ erg./sec.}$ for $R_{pc} \sim 10^{-2}$. Thus in order to get a luminosity of $\sim 10^{42} \text{ erg/sec.}$, comparable to the cold beam case, we need $(\beta_{\perp}^4 N_{10}) \sim 10^{-3}$. The transverse modulation $\beta_{\perp}$ can be expressed in terms of the luminosity L_i and frequency ω_i of the incident radiation as:

$$\beta_{\perp}^2 = \frac{e^2 E_i^2}{m^2 \omega_i^2 c^2} = \frac{e^2 L_i}{m^2 R_i^2 C^3 \omega_i^2} = \frac{2 \times 10^{-12} L_i 42}{\omega_{14}^2}$$

where $\omega_i = \frac{\omega_s}{42}$ has been used. Thus the condition $(\beta_{\perp}^4 N_{10}) \sim 10^{-3}$ can be satisfied either for extremely high densities and/or extremely low frequencies and therefore is unlikely to be satisfied in the infrared region of AGN. In the radio

region, e.g. for $\omega_{14} = 10^{-5}$, $N_{10} = 10$ and $Li_{42} = 1$, the Cerenkov-Raman process could operate and contribute to the overall radio emission which is also produced by synchrotron and plasma processes.

4. Conclusion

It is shown that, in AGN, sufficient infrared luminosities can be generated by electron beams of reasonable densities and small thermal spreads through stimulated Cerenkov process. This process falls in the category of nonthermal processes of radiation and must be taken into account while debating the issue of thermal vs nonthermal infrared emission. A more detailed study should include the frequency dependence of the dielectric constant of the dust in order to bring out the interrelation of the dust composition with the nonthermal continuum of AGN. The strong correlation (observed for a sample of active galaxies) between radio and infrared fluxes and luminosities has been attributed to an underlying relationship through physical processes like dust and gas heated by shocks produced by radio jets (Forbes and Ward, 1993). We believe that Cerenkov processes provide one more link between the radio and infrared radiation through their dependence on energetic electron populations.

Acknowledgement

I would like to thank Prof. A.M. Sessler of the Lawrence Berkeley Laboratory for his continued advice and support during the course of this work. I would also like to thank Prof. P.J. Wiita of the Georgia State University for a critical reading of the manuscript and for many useful suggestions.

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Fig.1 Cerenkov-Raman scattering

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