ACCELERATION AND RADIATION PROCESSES AROUND ACTIVE GALACTIC NUCLEI

V. KRISHAN

Indian Institute of Astrophysics, Bangalore, India

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Abstract. It is proposed that the region containing fast particles, electrostatic and electromagnetic fields, around active galactic nuclei is responsible for generating electromagnetic emissions from γ-rays to radio waves. The electrons are accelerated by Langmuir turbulence originating through the process of Raman forward scattering (RFS). The radiation mechanism is stimulated Raman backward scattering (RBS) where the fast electron beam loses energy by scattering over spatially periodic magnetic field. The spatially periodic magnetic field results from the magnetic modulational instability of the Langmuir waves. This model accounts well for the large luminosities observed in active galactic nuclei over γ-rays to radio waves and in addition it relates physically the emission regions at different wavelengths.

1. Introduction

Active galactic nuclei are observed to emit over a wide span of the electromagnetic spectrum. The electromagnetic radiation is emitted in the form of thermal and non-thermal continuum as well as line radiation in the optical and ultraviolet range. A luminosity of 10^{46}–10^{47} ergs s^{-1} is measured at γ-rays to optical frequencies. The synchrotron and the inverse Compton scattering are believed to be the standard emission mechanisms with their attendant problems of short electron life time and, therefore, the necessity of accelerating electrons over extremely short periods of time (Pacini and Salvati, 1978; Fabian and Rees, 1979). The total energy involved is 10^{60}–10^{62} ergs which corresponds to rest mass energy of 10^6–$10^8\, M_\odot\, c^2$, where $M_\odot$ is the mass of the Sun. It is believed that gravity is the source of this vast amount of energy since conversion efficiency of gravitational energy is high compared to that of some other processes like nuclear fusion. The central reservoir of energy is assumed to be a supermassive object of mass 10^8–$10^9\, M_\odot$, probably a black hole. The energy extraction is supposed to occur via accretion and or electrodynamic process (Pacini and Salvati, 1982). In the electrodynamic models, the particles are in a state of continuous acceleration since they are accelerated by the fields they emit. Taking this line of thought of Pacini and Salvati (1982), in this paper, we present Raman forward scattering (RFS) as the acceleration process and Raman backward scattering (RBS) as the emission mechanism in the atmospheres of active galactic nuclei. The rate of loss of energy of the electrons via RBS is matched with the rate of gain of energy in the Langmuir field generated by RFS. Demanding the same material to emit over the whole electromagnetic spectrum, one can determine the configuration of the emission region in terms of spatial variation of the density, the Lorentz factor γ and expansion velocity of the emitting plasma cloud. The assumption that the material involved in emission has been accreted,

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furnishes a very reasonable estimate of the accretion rate. We propose without giving details that the time variability in the emission results from the plasma density fluctuations caused by magnetohydrodynamic flows in the emission region.

2. Emission from γ-Rays to Radio Waves

We assume that a region around the central massive object, containing fast particles, electrostatic and electromagnetic fields emits from γ-rays to radio waves by a single mechanism of stimulated Raman backward scattering (RBS) (Krishan, 1983). The ingredients needed for this mechanism to operate are a relativistic electron beam and a spatially periodic magnetic field or an electromagnetic wave. Presently the case of spatially periodic magnetic field is considered.

2.1. Acceleration

We propose that the electrons are accelerated in the field of Langmuir waves. The generation of Langmuir field takes place via RFS wherein two electromagnetic waves (ω_0, K_0) and (ω_1, K_1) beat so that

$$\omega_0 - \omega_1 = \omega_p \quad \text{and} \quad K_0 - K_1 = K_p \,, \tag{1}$$

where (ω_p, K_p) are the plasma frequency and the wave vector of the longitudinal wave. The plasma oscillations are set by the pondermotive force generated by the beating of the two electromagnetic waves. In the case of RFS, one of the electromagnetic waves grows from thermal noise. The phase velocity V_p of the plasma wave is given as

$$V_p = \frac{\omega_p}{K_p} = \frac{\omega_0 - \omega_1}{K_0 - K_1} \sim c[1 - \omega_p^2/\omega_0^2]^{1/2} \,, \tag{2}$$

in the limit $\omega_p/\omega_0 \ll 1$. In this case plasma wave saturates via electron trapping at high amplitudes. Since $V_p \sim c$ the electrons will remain in phase with the wave for a long time and thus end up highly accelerated. There are several ways of estimating the magnitude of the electrostatic field generated through RFS (Tajima and Dawson, 1979; Tajima, 1982; Rees, 1982; and Joshi, 1982). Following Tajima (1982), one finds that

$$\nabla \cdot E = -4\pi e n' \tag{3}$$

or

$$E_{\mathrm{L}} = \frac{4\pi e n'}{K_p} = \frac{4\pi e n' V_p}{\omega_p} \sim \frac{4\pi e n' c}{\omega_p} = \frac{m\omega_p c n'}{e n} \,, \tag{4}$$

where the maximum value of the density fluctuation is $n' \sim n$. The rate change of energy of an electron in the field E_{L} is given by

$$\frac{\mathrm{d}w}{\mathrm{d}t} = e\mathbf{E}_{\mathrm{L}} \cdot \mathbf{V} \,; \tag{5}$$

and, therefore, the acceleration time t_a to gain energy γmc^2 becomes

$$t_a \simeq \frac{\gamma mc^2}{E_{\rm L} ce} = \frac{\gamma}{\omega_p} , \tag{6}$$

where n is the plasma density and γ is the relativistic Lorentz factor.

2.2. Generation of spatially periodic magnetic field

Modulational instabilities of the high amplitude Langmuir waves has been the subject of several recent investigations, Belkov and Tsytovich (1979, 1982) and Tsytovich (1983). Plasma oscillations with inhomogeneous phase distribution produce vortical currents which increase the spontaneously produced magnetic fields. This process is called magnetic modulational instability which excites magnetic fields with spatial periods ranging over $K_0 = \omega_p/c$ to $K_0 = \omega_p/V_{\rm th}$ with the amplitude $B = eE_{\rm L}^2/4mc\omega_p$ Belkov and Tsytovich (1979). One need not worry about the decay of this spatially periodic quasi-stationary magnetic field since it remains excited as long as the Langmuir field $E_{\rm L}$ remains re-inforced by the beating of the two electromagnetic waves.

2.3. Raman backward scattering

The source region of electromagnetic radiation consists of an ambient plasma of density n, a fast beam of electrons of density n_b and velocity $\sim C$, and a quasi-stationary spatially periodic magnetic field with spatial period $K_0 = \omega_p/c$ and amplitude $B = eE_{\rm L}^2/4m\omega_p c$. The rate of loss of energy by beam electrons via RBS has been discussed in Hasegawa (1978) and Krishan (1983) and is given as

$$\Gamma_{\rm L} = \frac{1}{\gamma} [2\beta_i^2 \omega_b^2 \gamma \omega_p]^{1/3} , \tag{7}$$

where

$$\beta_i = \frac{eB}{m\omega_p c} = \frac{1}{4}\left[\frac{eE_{\rm L}}{m\omega_p c}\right]^2 \sim \frac{1}{4} , \qquad \omega_b^2 = \frac{4\pi n_b e^2}{m} .$$

Now demanding that the rate of loss of energy of the electron, Equation (7) is equal to the rate of gain of energy, Equation (6), one finds that

$$\frac{1}{\gamma} [2\beta_i^2 \omega_b^2 \gamma \omega_p]^{1/3} = \omega_p/\gamma$$

or

$$\frac{n_b}{n} = 8/\gamma . \tag{8}$$

This relates electron beam density to the ambient plasma density. In order to determine the amount of power emitted through RBS, one has to invoke a saturation mechanism.

When the back-scattered power increases, it produces a large $\boldsymbol{\beta}_i \times \mathbf{B}_s$ electric field which traps the beam electrons and increases their thermal spread. The effective thermal speed produced by the trapping electric field is

$$V_{T_{\text{eff}}} = \left[\frac{2e\,|\beta_i|\;\;|B_s|}{k_b m}\right]^{1/2},$$

where k_b is the wave vector of the longitudinal wave excited in the beam electrons in RBS. One can take the saturation to occur when $k_b \sim \omega_b/V_{T_{\text{eff}}}$ because then the plasma wave (ω_b, K_b) suffers heavy damping and the process of scattering changes from Raman back scattering to inverse Compton scattering, i.e., the scattering of the spatially periodic field by the plasma wave (ω_b, K_b) (RBS) is replaced by the scattering of the spatially periodic magnetic field by single beam electrons (Compton scattering) (Hasegawa, 1978). Therefore, the maximum amplitude of the scattered field B_s (in the beam frame) is given as

$$\frac{\omega_b^2}{K_b^2} = \frac{2e\beta_i B_s}{mk_b} \quad \text{or} \quad B_s = \frac{m\omega_b^2}{2e\beta_i K_b}$$

and

$$K_b = \omega_b \left(\frac{\Delta\gamma}{\gamma}\, c\right)^{-1}, \tag{9}$$

where $(\Delta\gamma/\gamma)c$ is the thermal spread in the beam electrons in the beam frame. The total power emitted in the frame in which electron beam has a velocity close to c is

$$L = \frac{c}{4\pi}\, 4B_s^2\gamma^2 A = \left(\frac{\Delta\gamma}{\gamma}\right)^2 \frac{mc^3}{\beta_i^2}\, \gamma^2 n_b A\,, \tag{10}$$

where A is the area of cross-section of the electron beam. We know that in RBS the emission frequency of the scattered wave ω_s is

$$\omega_s = 2\gamma^2 K_0 c = 2\gamma^2 \omega_p\,.$$

By equating this to the maximum frequency of emission ω_{cr}, one finds that

$$\omega_s = 2\gamma^2\omega_p \lesssim \omega_{cr} = \frac{\gamma^2\omega_b}{\Delta\gamma}$$

or

$$\left(\frac{\Delta\gamma}{\gamma}\right)^2 \leq \frac{\omega^2 b}{4\gamma^2\omega_p^2}\,. \tag{11}$$

Choosing $(\Delta\gamma/\gamma)^2 \sim \omega_b^2/4\gamma^2\omega_p^2$ and using Equation (8), we find the power emitted or the luminosity of the source to be

$$L \sim 10^7\, \frac{nA}{\gamma^2}\,, \tag{12}$$

and the emission frequency $\omega = 2\gamma^2\omega_p$. It is proposed that the atmospheres of active galactic nuclei emit the above luminosity L at a frequency of emission ω, Equation (12). Thus high-plasma density region gives rise to high-frequency radiation like γ-rays and low-density regions are the sites of low-frequency emission. The cross section of the electron beam A varies with density and emission frequency. In fact, one observed that for fixed values of γ, the luminosity L has the same value at all frequencies provided that the product (nA) is a constant. This defines a law for density variation, i.e., $n \propto (r^2)^{-1}$ for circular cross section. This is the familiar law of density variation for a uniformly expanding region. Thus, if we model the emission region around active galactic nuclei with plasma density varying inversely proportional to the cross-section area we have a mechanism for generating luminosities which are comparable at γ-rays, X-rays, optical, and radio wavelengths. Since observationally, one does find a decline in luminosity with frequency, although most often $L_{\gamma\text{-ray}} > L_{\text{X-ray}} \gtrsim L_{\text{optical}} > L_{\text{radio}}$, we have tried to model the spatial variation of the plasma density n, the Lorentz factor γ and, hence, that of luminosity L. Let us assume the following spatial variations:

$$n = n_r \left(\frac{R_r}{r}\right)^{\beta+2}, \qquad \gamma^2 = r_r^2 (R_r/r)^{\alpha},$$

$$\omega = 2\gamma_r^2 \sqrt{30} \times 10^4 \sqrt{n_r} \cdot (R_r/r)^{\alpha+1+\beta/2} = \omega_r \left(\frac{R_r}{r}\right)^{\alpha+1+\beta/2} \tag{13}$$

and

$$L = 10^7 \frac{n_r A_r}{r_r^2} \left(\frac{R_r}{r}\right)^{\beta-\alpha},$$

where $A \sim r^2$ and $A_r \sim R_r^2$ is the cross-section area of the γ-ray emission region; n_r, the density; and γ_r^2, the Lorentz factor for γ-ray emission region. The case $\alpha = \beta = 0$ corresponds to the case of uniformly expanding region discussed above. Let us adopt $\omega_r = 10^{23}\ \text{s}^{-1}$ and $\gamma_r^2 = 10^9$: this gives $n_r = 10^{18}\ \text{cm}^{-3}$ and $L_r = 10^{46}\ \text{ergs s}^{-1}$ for $A_r = R_r^2 = 10^{30}\ \text{cm}^2$. The volume of emission can be determined from the total energy emitted – i.e., $10^{46+15}\ \text{ergs} = n_b \gamma mc^2 \Omega = 8 n_r mc^2 R_r^2 l_r$ gives $l_r = 10^{18}$ cm and $\Omega^{1/3} \sim 10^{16}$ cm.

We discuss the spatial variation of the luminosity and sizes of emission region for two choices of the indices α and β.

(i) $\alpha = \beta = 1$

L is the same at all frequencies

$$n = n_r (R_r/r)^3 ; \qquad r^2 = r_r^2 (R_r/r) \quad \text{and} \quad \omega = \omega_r \left(\frac{R_r}{r}\right)^{2.5};$$

we find for:

$$\omega = \omega_x = 10^{19}, \qquad R_x^2 \sim 10^{33.2}\ \text{cm}^2,$$

$$n_x \sim 1.58 \times 10^{13}\ \mathrm{cm}^{-3}, \qquad \Omega^{1/3} \sim 10^{17}\ \mathrm{cm},$$

$$\omega = \omega_{\mathrm{opt}} = 10^{15}, \qquad R^2_{\mathrm{opt}} \sim 10^{36.4}\ \mathrm{cm}^2,$$

$$n_{\mathrm{opt}} \sim 10^{8.4}\ \mathrm{cm}^{-3}, \qquad \Omega^{1/3} \sim 10^{19}\ \mathrm{cm},$$

$$\omega = \omega_R = 10^{10}, \qquad R^2_R \sim 10^{40.4}\ \mathrm{cm}^2,$$

$$n_R \sim 10^{2.4}\ \mathrm{cm}^{-3}, \qquad \Omega^{1/3} \sim 10^{21}\ \mathrm{cm}.$$

From the above estimates, we find that the effective linear sizes at optical and radio wavelengths are comparable to the observed sizes. Apparao (1978) and Swanenburg *et al.* (1978). To model the variation of luminosity with frequency, we have to choose unequal values of α and β. We choose:

(ii) $\alpha = \frac{2}{3}$, $\beta = \frac{5}{3}$ so that

$$n = n_r(R_r/r)^{11/3}, \qquad r^2 = r_4^2(R_r/r)^{2/3}, \qquad \omega = \omega_r\left(\frac{R_r}{r}\right)^{2.5}$$

and

$$L = L_r(R_r/R).$$

We find for

$$\omega = \omega_r = 10^{23}, \qquad R_r^2 = 10^{30}\ \mathrm{cm}^2, \qquad L_r = 10^{46}\ \mathrm{ergs\ s}^{-1},$$

$$\omega = \omega_x = 10^{19}, \qquad R_x^2 = 10^{33.2}\ \mathrm{cm}^2, \qquad L_x = 2.5 \times 10^{44}\ \mathrm{ergs\ s}^{-1},$$

$$\omega = \omega_{\mathrm{opt}} = 10^{15}, \qquad R^2_{\mathrm{opt}} = 10^{36.4}\ \mathrm{cm}^2, \qquad L_{\mathrm{opt}} = 10^{43}\ \mathrm{ergs\ s}^{-1},$$

$$\omega = \omega_R = 10^{10}, \qquad R^2_R \sim 10^{40.4}\ \mathrm{cm}^2, \qquad L_R \simeq 10^{41}\ \mathrm{ergs\ s}^{-1}.$$

Apparao (1978) has listed the values of luminosities at various frequencies and the estimates shown above are in good agreement. A plot of $\log(L/\omega)/(L_r/\omega_r)$ vs $\log(\omega/\omega_r)$ is shown in Figure 1 and demonstrates the expected behavior of the flux vs frequency for emission from active galactic nuclei. If one assumes that the material responsible for emission has been accreted, one can relate luminosity and the accretion rate as

$$L = \frac{10^7}{r_r^2}\left(\frac{\mathrm{d}M}{\mathrm{d}t}\, t_{\mathrm{age}}\right)\frac{1}{m_p l_r} = 10^5\ \frac{\mathrm{d}M}{\mathrm{d}t}\, t_{\mathrm{age}}$$

or

$$\frac{\mathrm{d}M}{\mathrm{d}t} \sim 10^{26}\ \mathrm{g\ s}^{-1} \quad \text{for} \quad L \sim 10^{46}\ \mathrm{ergs\ s}^{-1},$$

which is satisfactory (cf. Longair, 1981). A comment about the spatial variation of density, Equation (13) is in order. Now, we know that mass conservation in a hydrodynamic system is nAV = constant where V is the velocity of expansion. For the case $\beta = 0$ and $A \sim r^2$, we get V = constant and this corresponds to the expansion with

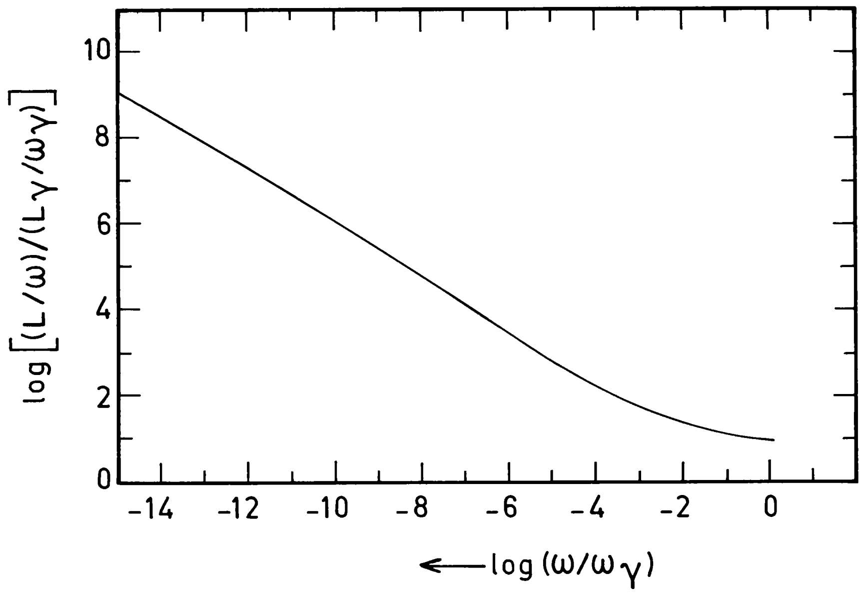

Fig. 1. A plot of $\log[(L/\omega)/(L_r/\omega_r)]$ vs $\log(\omega/\omega_r)$.

uniform velocity. For $\beta = \frac{5}{3}$, we get $V \propto r^{5/3}$ which corresponds to the case of expansion velocity increasing with distance. One could recall here the Parker flow in which the case $\beta = 0$ corresponds to the flow far from the central object and the case $\beta \neq 0$, $r \neq 0$ corresponds to the flow near the central object (see Parker, 1965).

We propose that time variability of emission is caused by the density fluctuation that result from mangeto-hydrodynamic flows. One knows that the length scale of these density fluctuations ($\delta n \sim n$) varies from $R/3$ to the collisional mean free path of a proton, where R is the radius of the plasma region. The time-scale of these fluctuations varies from R/V to the proton-proton collision time. Thus, in general, one would expect to observe time variability over a large range of periods in a given region at a given frequency of emission. The largest period of variation, however, will be proportional to the size of emission region and inversely proportional to the emission frequency. The details of this mechanism of time variability will be published elsewhere.

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