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Emission Mechanism of Extragalactic X-ray and Radio Sources

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The processes of stimulated Raman Scattering (SRS) and stimulated Compton scattering (SCS) are investigated in order to provide a possible emission mechanism for the extragalactic X-rays and radio sources. The system proposed is a relativistic plasma beam propagating transverse to a static periodic magnetic field. The role of the incident pump radiation, e.g. the microwave background, has been replaced by the static spatially periodic magnetic field. It is shown that by varying the spatial periodicity of the magnetic field, one could generate X-rays to radio waves by a single mechanism of SRS and/or SCS.

The three mechanisms proposed for the generation of X-rays on the galactic scale are (1) thermal bremstrahlung, (2) synchrotron radiation and (3) Compton scattering, Burbidge (1970), Burbidge (1973), Gursky and Schwarte (1977) and Fabian and Rees (1979). Thermal bremstrahlung accounts fairly well for a significant part of the flux in SCOX-1 and the polarization measurements confirm the synchrotron mechanism to be active in the X-ray band in Crab nebula (Novick *et al.*, 1972). In the extragalactic sources, there is not enough evidence to prefer one mechanism over the other. Thermal bremstrahlung received attention due to the detection of Fe line emission feature at ~ 6 Kev, which requires a gas of particle density $10^{-3}/\mathrm{cm}^3$ and a temperature of 10^7–10^8 °K (Novick *et al.*, 1972, Mitchell *et al.*, 1975 and Serlemitsos *et al.*, 1977). At the same time identification of the radio sources with X-ray sources advocates the presence of relativistic electrons. These relativistic electrons can comptonize the soft photons of the microwave background radiation into X-rays. The radio emission associated with the X-ray sources could result from synchrotron process in the presence of magnetic fields of the order of a microgauss or less, Brecher and Burbidge (1972), Bridle and Feldman (1972) and Burbidge (1970). The X-ray luminosity Lx is proportional to the energy density of the background microwave radiation and the ratio luminosity Lr is proportional to the energy density of the ambient magnetic field ($B^2/8\pi$) Felton and Horrison (1966). Grindlay (1975) and Grindlay *et al.*, 1975 have observed and interpreted the emissions from radio wavelengths' to 10^{11} ev γ-rays in Centaurus A. A two component model is proposed where the low frequency of the spectrum is generated by synchrotron and the high energy photons by compton scattering of the same synchrotron electrons into the long wavelength photons. The two components are characterized by two different values of the angular sizes and magnetic field strengths. Though the X-ray emission from clusters of galaxies does not seem to be correlated with extended radio and optical halos observed in the cluster, various emissions occur in the same spatial region, thus exacting a common underlying phenomenon Giacconi (1974, 1976). The X-ray to radio luminosity ratio for radio clusters may range from 10^{-3} for virgo to about one in Perseus, Kellogg (1972). This is in contradiction with the conclusion of Brecher and Burbige (1972) Burbidge (1973) where the argument that X-ray luminosity is much larger than radio luminosity is used to relate the energy density of the microwave background radiation to the ambient magnetic field.

In this paper, we suggest an alternative way of looking at the process of comptonization, the roles of the microwave background radiation density and the ambient magnetic field B. A stationary plasma system in the field of an electromagnetic wave is equivalent to a plasma beam travelling with relativistic speed through a static periodic magnetic field. The direction of the beam velocity is transverse to that of the magnetic field, Hasegawa (1978) and Colson (1977). We propose that the system responsible for the generation of X-ray and radio rays consists of a fast relativistic plasma beam travelling transverse to a static periodic magnetic field. This system in the beam frame becomes a stationary plasma (beam in the beam frame) plus an electromagnetic wave with frequency $w_i = \gamma k_o V_o$, the wave vector $K_i = \gamma k_o$ and an amplitude $E_i = \gamma(V_o/C)B_L$, where $\lambda_o = 2\pi/K_o$ and B_L are the spatial periodicity and the magnitude of the magnetic field in the laboratory frame, $\gamma = (1 - V_o^2/C^2)^{-(1/2)}$, V_o is the velocity of the electron (plasma) beam, (The laboratory frame is the one with plasma beam and a static periodic magnetic field). The relationship between various quantities can be determined through Lorentz transformations, Hasegawa (1978). Hence system of plasma beam in a static periodic magnetic field has been transformed to the one where an electromagnetic wave characterized by (w_i, k_i, E_i) is incident on relativistic electrons and ions or positrons. Different treatments of the (neutralized) electron beam plasma system in a static periodic magnetic field, in order to explain radio emission from the sun, have been given earlier, Krishan (1980) and Krishan (1982). Various proposals have been put forward for the formation of relativistic plasma beams from the central nuclei at the galactic and extragalactic levels (Blandford (1976), Blandford and Rees (1974) and Rees (1978)). One notices that in the above scenario, the strength of the ambient magnetic field B_L gets related to the energy density of the electromagnetic radiation E_i. Thus the main point is that the ambient magnetic field can be visualized as an electromagnetic wave in a frame of reference moving with a speed close to the speed of light C. The role of the incident frequency (for example the frequency of the microwave background radiation) is taken by the quantity ($K_o c$). One may observe that the magnitude of the background radiation density U (may it be Crab nebula, microwave background or Radio galaxy) is comparable to the magnetic field density i.e. $U \simeq B^2/8\pi$. The compton scattered photons will have a frequency $\gamma k_o C$ in the beam frame and $\gamma^2 k_o C$ in the laboratory frame. It is by varying k_o, that we plan to generate the whole spectrum from X-rays to radio waves by a single mechanism of comptonization. The requirement is that the spatial period λ_o is different in different regions, λ_o is small in X-ray sources and large in radio sources, continuously increasing towards regions of low frequency emission. In fact one could get a complete spatial map of the magnetic field from X-ray sources to radio sources. Since a single mechanism is operative from X-rays to radio waves, one can exercise a better control over the various physical parameters of the system. We would also like to point out that the compton scattering could occur in two ways: (1) by an excitation of a single particle state, called the stimulated compton scattering (SCS) and (2) by an excitation of a plasmon, the collective plasma oscillation of the electrons and ions called the Stimulated Raman scattering and the stimulated Brillouin scattering respectively, Hasegawa (1978), Colson (1977) and Brueckner and Jorna (1974). The gain in the two cases of SCS and SRS differs substantially. Since in an equal temperature plasma, the ion-acoustic mode is highly damped, we will here consider only SRS. In the case, where the neutralization is provided by positrons, the following treatment is applicable with the effective plasma frequency equal to $\omega_p^2\,(1 + m_e/m_p)$, where $m_e \sim m_p$ is the mass of the positrons. The details of the procedure for calculation of the growth rate or the rate at which the electrons lose energy are given in Hasegawa (1978).

Here we present some of the results and explore their applicability to the extra-galactic X-ray sources and the associated radio sources. In the laboratory frame, the electron energy loss rate for SRC is

$$\left[\frac{1}{E}\frac{dE}{dt}\right]_L^R = \frac{1}{t_L^R} = 1.6\sqrt{12} \times 1.7 \times 10^7 \left[\frac{U\omega_p}{\gamma k_o c}\right]^{1/2} \quad \text{for}\,(\omega_c/k_o c) \ll \left[\frac{\omega_p}{\gamma k_o c}\right]^{1/2} \tag{1}$$

where $w_c = 1.6 \times 10^7 B = 1.6 \times \sqrt{12} \times 10^7\sqrt{U}$ and $\omega_p^2 = (4\pi N e^2/m_e)$ is the plasma frequency. For $\omega_c/k_o c \gg [\omega_p/\gamma k_o c]^{1/2}$ one finds

$$\frac{1}{t_L^R} = \frac{2}{\gamma}\left[\frac{\omega_c^2 \omega_p^2 \gamma}{k_o c}\right]^{1/3} \tag{2}$$

For SCS, one gets

$$\frac{1}{t_L^C} = 0.4\frac{\omega_c^2}{(k_o c)^3}\frac{1}{(\Delta\gamma/\gamma)^2}\frac{\omega_p^2}{\gamma^2} \quad \text{for} \quad \frac{\omega_c}{k_o c} < \frac{\Delta\gamma}{\gamma} \tag{3}$$

$$= 0.3\frac{\omega_c}{(k_o c)^2}\frac{\omega_p^2}{\gamma^2}\left(\frac{\gamma}{\Delta\gamma}\right)^{3/2} \quad \text{for} \quad \frac{\omega_c}{k_o c} > \frac{\Delta\gamma}{\gamma} \tag{4}$$

where $\Delta\gamma$ is given by thermal spread of electrons V_T in the beam frame, $V_T \sim c\,\Delta\gamma/\gamma$. The total luminosity L is given by $L = VN_e\langle dE/dt\rangle_L$, where V is volume of the source. For the problem considered here, we find that formulae (1) and (3) are applicable. One can calculate the life time of an electron and the luminosity for SRS and SCS for values of the parameters appropriate to the sources. We find that for X-rays ($k_o c = 10^{15}$/sec., $U \sim 10^{-12}$ ergs/cm^3, $\Delta\gamma/\gamma \sim 10^{-2}$, $\gamma = 30$, $\omega_p^2 = 10^{19}/\text{sec}^2$). $t_L^R \sim 30$ sec. and $L_x^R \sim 10^{45}$ ergs/sec. for $V = 10^{42}$ cm^3. The Compton life time for the same parameters is $t_L^C \sim 10^{22}$ sec. and one needs $V \sim 10^{62}$ cm^3 in order to get $L_x^C \sim L_x^R$. At low electron densities e.g. for $\omega_p^2 = 3 \times 10^6/\text{sec}^2$ for $N_e \sim 10^{-3}/\text{cm}^3$., with no change in the values of other parameters one finds $t_L^R \sim 10^5$ secs and $V \sim 10^{57}$ cm^3 gives $L_x^R \sim 10^{45}$ ergs/sec. At low electron density, the Compton life time increases to 10^{30} secs. but an extremely large $V \sim 10^{70}$ cm^3 is required to get $L_x^C \sim 10^{45}$ ergs/sec.

For large values of γ, a smaller value of $k_o c$ will suffice to generate x-ray frequencies. For example for $\gamma \sim 10^4$, $k_o c = 10^{10}$/sec. $U \sim 10^{12}$ ergs/cm^3, $\Delta\gamma/\gamma \sim 10^{-2}$, $\omega_p^2 = 10^{19}/\text{sec}^2$, we find $t_L^R \sim 1.77$ secs. and $L_x^R \sim 10^{45}$ ergs/sec. for $V = 10^{38}$ cm^3. The Compton life time for the same parameters is $t_L^C \sim 10^{12}$ sec. and one need $V = 10^{51}$ cm^3 in order to get $L_x^C \sim L_x^R$. At low densities i.e. for $Ne \sim 10^{-3}$ cm^3 with $\gamma = 10^4$, we get $t_L^R \sim 10^3$ secs and $V \sim 10^{53}$ cm^3 gives $L_x^R \sim 10^{45}$ ergs/sec. The Compton life time for this case $t_L^C \sim 10^{26}$ secs and a volume of $\sim 10^{76}$ cm^3 is required to get $L_x^C \sim 10^{45}$ ergs/sec.

At radio frequencies, say around 9 MHZ ($k_o c = 10^4$/sec, $U \sim 10^{-12}$ ergs/sec, $\Delta\gamma/\gamma = 10^{-2}$, $\gamma = 30$, $\omega_p^2 = 10^{19}/\text{sec}^2$) $t_L^R \sim 10^{-3}$ sec. and a source volume of $10^{38}\,\text{cm}^3$ can give a radio luminosity $L_r^R \sim 10^{45}$ ergs/sec. The Compton life time is found to be extremely small $\sim 10^{-12}$ sec and one would not know how to replenish or reaccelerate electrons at such a fast rate. At low electron density ($N_e = 10^{-3}/\text{cm}^3$) $t_L^R \sim 3$ sec. and $V \sim 10^{53}\,\text{cm}^3$ gives $L_r^R \sim 10^{45}$ ergs/sec. The Compton life time $t_L^R \sim 40$ sec. and a source volume of $10^{55}\,\text{cm}^3$ gives $L_r^C \sim 10^{45}$ ergs/sec. Thus one concludes that SRS as well as SCS can account for X-rays in high electron density regions, but only SRS is efficient at low electron densities (due to its collective nature). Radio emission can be accounted by both SRS and SCS at low electron densities, but at high electron densities SRS seems to be more likely. We have given examples for only two frequencies of emission, at 10^{18}/sec. and 9 MHz. In this picture, it is possible to extend these calculations over the whole-spectrum from hard X-ray to very low frequencies, enabling in the process the mapping of the spatial structure of the magnetic field in X-ray, optical and radio regions. The strength of the magnetic field could be allowed to have a lower value without upsetting other quantities. In fact a whole lot of information can be attained about the size of the source, periodicity and the magnitude, of the magnetic field, the electron density, the polarization of the scattered radiation (usually circular) and the maximum saturation intensity of the scattered radiation, over the whole spectral range. The values of the various physical quantities chosen here do not refer to any one particular object but are a representative of a class of these objects. The numerical estimates for the case of high magnetic field density (equations (2) and (4)), which would correspond to the multiple Compton scattering Fabian and Rees (1979) have not been given here.

The structure of the magnetic field assumed here may be produced by the fourier analysis of an otherwise space dependent random fields Perola (1981). The presence of hydro magnetic turbulence as in the case of crab nebula can modify the field and introduce periodicities in space and time Melrose (1980). The frequency of the MHD waves will in general be much smaller than $k_o c$ since the phase velocity of the MHD waves is very small compared to C. Such a field may compose of multiperiodic and non-periodic components in general. If the field is just an inhomogeneous function of space, then the well known effects of curvature radiation, gradient drifts and the trapping of the particles will be present. The presence of multi-periodicity in the magnetic field results in radiation at the high harmonic of the corresponding fundamental frequency. The variable period field also facilitates the control of the rate of thermal spread and the rate of loss of electron energy of the electron beam in a favourable manner, Kroll *et al.*, 1980. The presence of helical magnetic fields force free or otherwise has been invoked in many astrophysical situations and observed in some as for example the solar magnetic fields. It may be noted that a transverse periodic field of the type assumed here also satisfies the equations $\nabla \times B = k_o B$ and $\nabla \cdot B = 0$. Such field configurations result from the currents following parallel to the magnetic field in a plasma in which case the wave vector k_o is related to the current density through the equation $\nabla \times B = k_o B = 4\pi/c\, J$. This gives $K_o c = 4\pi J/B$. For $B \sim 10^{-5}$ gauss, a current density $J \sim 3 \times 10^{-12}\,\text{amp/cm}^2$ gives $k_o c = 10^4$/sec. and $k_o c = 10^{10}$/sec. for $J \sim 3 \times 10^{-6}\,\text{amp/cm}^2$. One must of course worry about the stability of the plasma in the presence of the current which gives rise to a transverse component of the magnetic field. This restricts the current to flow in a sheath of finite thickness. Thus for example, in order to keep $B_\perp \sim B_\parallel \sim 10^{-5}$ gauss the thickness of the current sheath $\delta \sim c/4\pi B_\perp/J$ which is found to be 2×10^6 cm for $J = 3 \times 10^{-12}$ amp/cm^2 and $\delta \sim 10$ cm for $J \sim 3 \times 10^{-6}$ amp/cm^2. Thus narrow current channels or filaments can control the generation of the transverse magnetic field and ensure stability of the system. The generation of space and time dependent periodic magnetic field is shown to be possible through modulational instability of strong electrostatic wave turbulence Belkov and Tsytovich (1982) and a current carrying plasma does support electrostatic turbulence. In conclusion, it is possible in principal to generate spatially periodic magnetic field through one of the processes mentioned above. The magnitudes of the various parameters, the feasibility of current sheaths of centimeter widths are some of the more practical questions which need to be addressed. The high spatial resolution observations in astrophysical objects do indicate towards a complex nature of the magnetic field configuration, as for example Miley (1980) suggests that the three dimensional configuration of the magnetic field in radio galaxies may be of helical form. The piece of work presented here is only a maiden attempt to study the role of the complexities of the magnetic field structure in emission processes in astrophysical situations.

Applicability of the present mechanism, using the measured properties of the X-ray and radio sources, as well as the high magnetic energy density case will be discussed elsewhere in a more detailed paper.

REFERENCES

Belkov, S. A. and Tsytovich, V. N. (1982) *Phys. Scr.*, **25**, 416.
Blandford, R. D. and Rees, M. J. (1974), *Mon. Not. R. Astron. Soc.*, **169**, 395.
Blandford, R. D. (1976) *Mon. Not. R. Astron. Soc.*, **176**, 465.
Brecher, K. and Burbidge, G. R. (1972), *Nature*, **237**, 440.
Bridle, A. H. and Feldman, P. A. (1972), *Nature Phys. Sci.*, **235**, 168.
Brueckner, K. A. and Jorna, S. (1974), *Rev. Mod. Phys.*, **46**, 325.
Burbidge, G. R. (1970), *Astrophys. J., Lett.*, **159**, L105.
Burbidge, G. R. (1970), *Annu. Rev. Astron. Astrophys.*, **8**, 369.
Burbidge, G. R. (1973), IAU Symp. No. 55, 199.
Colson, W. B. (1977) "Novel Sources of Coherent Radiation", p. 157, Edited by Stephen F. Jacobs, Murray Sargent III and Marlan O. Scully, Addison Wesley Publishing Company, Inc.
Fabian, A. C. and Rees, M. J. (1979), in "X-ray Astronomy" ed. W. A. Baity and L. E. Peterson (Pergamon), 381.
Felton, J. and Horrison, P. (1966), *Astrophys. J.*, **146**, 686.
Giacconi, R. (1979), X-Ray Astronomy edited by R. Giacconi and and H. Gursky Chap. H and (1976), The Physics of Non-Thermal Radio Sources edited by Giancarlo Setti, p. 229.
Grindlay, J. E., 1975, *Astrophys. j.*, **199**, 49.
Grindlay, J. E., Schnopper, H., Schreier, E. J., Gursky, H. and Parsignault, D., *Astrophys. J., Lett.*, **201**, L133.
Gursky, H. and Schwarte, D. A. (1977), *Annu. Rev. Astron. Astrophys.*, **15**, 541.
Hasegawa, A. (1978), *The Bell Syst. Tech. J.*, **57**, No. 8, 3069.
Kellogg, E. M. 1973, X-Ray Astronomy edited by R. Giacconi and H. Gursky p. 321.
Krishan, V. (1980), *Plasma Phys.*, **22**, 163.
Krishan, V. (1982) *Plasma Phys.*, **24**, 31.
Kroll, N. M., Morton, P. L. and Rosenbluth H. N. 1980, Free Electron Generators of Coherent Radiation p. 89.
Melrose, D. B. (1980), Plasma Astrophysics Vol. **2**, p. 66.
Miley, G. 1980 *Annu. Rev. Astron. Astrophys.*, **18**, 165.
Mitchell, R. J., Culnane, J. L., Davidson, P. J. N. Ives, J. C., (1975), *Mon. Not. R. Astron. Soc.*, **175**, p. 29.

Novick, R., Weisskopf, M. C., Berthelsdort, R., Linke, R., and Wolff, R. S. (1972), *Astrophys. J. Lett.*, **174**, L1.
Perola, G. C. 1981, *Fundam of Cosmic Phys.*, **7**, 59.
Rees, M. J. (1978), *Mon. Not. R. Astron. Soc.* **184**, p. 61.
Serlemitsos, P. J., Smith, B. W., Boldt, E. A., Holt, S. S., and Swank, J. H. (1977), *Astrophys. J., Lett.*, **211**, L63.