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Raman scattering of the synchrotron self-absorbed radiation in accretion discs

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Summary. The quasar non-thermal continuum in the radio region can undergo Raman scattering in the accretion disc plasma around the central black hole provided that the frequency and the wave vector matching and the threshold conditions are satisfied. The scattered radiation has a frequency $\omega_0/2 \sim \omega_p$ where ω_0 is the frequency of the incident radiation and ω_p is the electron plasma frequency. The spectral shape of the scattered radiation is significantly different from that of the incident radiation. It is proposed that the observed spectral shape of the radio radiation may be accounted for by including the effects of Raman scattering.

1 Introduction

The discrepancies between the observed flat spectra (typically $\alpha=0.03$–0.5 with $F_\nu \propto \nu^{-\alpha}$) of the compact extragalactic radio sources and the predictions of the homogeneous synchrotron models are usually explained by invoking multiple components, inhomogeneity and/or specialized spectra of the energetic electrons (Spangler 1982). We propose here that stimulated Raman scattering may be another important source of spectral modification in the compact radio sources. Stimulated Raman scattering is the scattering of the incident electromagnetic radiation by the electron plasma waves excited in the plasma, which also serves as the scattering medium. It will be shown that the plasma in the accretion disc surrounding a supermassive black hole provides the right conditions for Raman scattering of the radio radiation. It is found that the spectral shape of the scattered radiation is significantly different from that of the incident radiation, and is close to what is observed.

2 Stimulated Raman scattering in an accretion disc

We investigate the interaction of the non-thermal continuum emitted from the central object with the plasma of electron density n surrounding the black hole. Parametric instabilities are known (Liu & Kaw 1976) to be excited when intense electromagnetic radiation at (ω_0, $\mathbf{K}_0$) propagates through an underdense plasma ($\omega_0 > \omega_p$). Energy and momentum conservation give

$$\omega_0=\omega_1+\omega_2, \qquad \mathbf{K}_0=\mathbf{K}_1+\mathbf{K}_2, \tag{1}$$

where at least one of the decay waves is an electron plasma wave (ω_e) satisfying the dispersion relation

$$\omega_e^2=\omega_p^2+3\mathbf{K}_p^2V_e^2,$$

where

$$\omega_p=\left(\frac{ne^2}{\varepsilon_0 m_e}\right)^{1/2}, \qquad V_e=\left(\frac{K_B T_e}{m_e}\right)^{1/2} \tag{2}$$

and K_p is the wave vector of the electron plasma wave. Disc surface temperatures $T_e \sim 3\times10^4$ K are reasonable, but higher values are expected in the disc interior. There are two kinds of instabilities which can be excited in an underdense plasma. The first is the two-plasmon decay instability, where ω_1 and ω_2 are both electron plasma waves so that the frequency matching is possible only if $\omega_0 \simeq 2\omega_p$. This occurs near the quarter critical density such that $n \sim n_c/4$ where n_c is the critical density defined from $\omega_0=\omega_p$. The second is the stimulated Raman scattering (SRS) instability, which results from the resonant decay of an incident photon into a scattered photon plus an electron plasma wave. Since the minimum frequency of an electromagnetic wave in a plasma is ω_p, this process can occur for $n \leqslant n_c/4$ or $\omega_0^2 \geqslant 4\omega_p^2$. Parametric instabilities are a threshold phenomena. For an incident electromagnetic wave of the form $\mathbf{E}_0=E_0\,\hat{\mathbf{e}}\cos(\mathbf{K}_0\cdot\mathbf{x}-\omega_0 t)$, the threshold for Raman backscattering in a homogeneous underdense plasma is given as

$$\left(\frac{V_0}{c}\right)^2 \geqslant 4\left(\frac{\Gamma_p}{\omega_p}\right)\left(\frac{\Gamma_s}{\omega_0}\right) \tag{3}$$

where $V_0=eE_0/m_e\omega_0$ is the quiver velocity of an electron in the field E_0 of the incident wave,

$$\Gamma_p=(\sqrt{\pi}/2K_p^3\lambda_D^3)\omega_p\times\exp\left[-\frac{1}{2K_p^2\lambda_D^2}-\frac{3}{4}\right]+\nu_c$$

is the total damping rate of the electron plasma wave, λ_D is the Debye length, $\Gamma_s=(\omega_p^2\nu_c/2\omega_s^2)$ is the collisional damping rate of the scattered wave, and ν_c is the electron–ion collision frequency (Liu & Kaw 1976). The growth rate for the stimulated Raman scattering is given by:

$$\gamma_{SRS}=\frac{V_0}{c}(\omega_p\omega_0)^{1/2} \quad \text{for} \quad \left(\frac{V_o}{c}\right) \ll \left(\frac{\omega_p}{\omega_0}\right)^{1/2}.$$

The scattered radiation is exactly at the electron plasma frequency for $\omega_0 \simeq 2\omega_p$.

2.1 FLUX DENSITY OF THE SCATTERED RADIATION

In order to estimate the energy content of the scattered radiation, one has to invoke a saturation mechanism for the stimulated Raman scattering instability. When the amplitude of the Langmuir wave of the SRS instability grows large enough to trap electrons in its field and therefore increase the effective electron thermal speed, the Langmuir wave is Landau-damped and the Raman scattering stops. The saturation is reached when the growth rate of SRS is equal to the damping rate of the Langmuir wave, i.e. (Krishan 1983; Hasegawa 1978; Krishan & Wiita 1986)

$$\gamma_{SRS}=\Gamma_p(E_p^2), \tag{5}$$

where $\Gamma_p(E_p^2)$ is the Landau-damping rate which is a function of the energy density of the SRS electron plasma wave. For this particular case of SRS where $\omega_0=2\omega_p$, equal amounts of energy go to the scattered electromagnetic radiation and the electron plasma wave as dictated by the Manley–Rowe relations for conservation of wave action (Figueroa *et al.* 1984). Substituting for

Γ_p, one calculates the energy density in the scattered electromagnetic wave as follows:

$$\Gamma_p(E_p^2)=\frac{\sqrt{\pi}\omega_p}{2K_p^3\lambda_{D\,eff}^3}\exp\left(-\frac{1}{2K_p^2\lambda_{D\,eff}^2}-\frac{3}{4}\right),$$

$$\lambda_{D\,eff}=\frac{V_{eff}}{\omega_p},\qquad V_{eff}=\left(\frac{2eE_p}{mK_p}\right)^{1/2},$$

$K_p \simeq 2K_0$ for backscattering.

From equation (5) one gets

$$x^3\exp\left(-\frac{x^2}{4}-\frac{3}{4}\right)=\frac{2\sqrt{2}}{\sqrt{\pi}}\left(\frac{V_0}{c}\right), \tag{6}$$

where

$$x=\frac{V_{ph}}{V_{eff}};\qquad V_{ph}=\frac{\omega_p}{K_p}.$$

After finding the value of x from equation (6), one determines the energy density of the electron plasma wave, which is also the energy density of the scattered radiation, as

$$E_s^2=E_p^2=\frac{m^2c^2}{64e^2}\frac{\omega_p^2}{x^4}. \tag{7}$$

The luminosity L_s and the flux density F_s can be determined as $L_s=cR_s^2E_s^2$ and $F_s=L_s/\omega_p$, where R_S is the size of the scattering region. The flux density of the scattered radiation from a region of size R_S with electron plasma frequency ω_p is given by

$$F_s=\frac{m^2c^3}{64e^2}R_s^2\frac{\omega_p}{x^4}, \tag{8}$$

where x is to be determined from equation (6). The spectral shape of the incident radiation spectrum is taken to be the self-absorbed synchrotron radiation with a spectral index of 5/2, i.e. $F_0 \propto \omega^{5/2}$. Then one finds from equation (6) that

$$x^4(\omega_9)\simeq(x^4)_{0.1}\left(\frac{\omega_9}{0.1}\right)^{-0.22}, \tag{9}$$

where

$$F_0(\omega_9)=0.18\times10^{29}\omega_9^{5/2}\ \mathrm{W\ Hz^{-1}},$$

$$E_0^2=\frac{\omega_0F_0}{cR_0^2}=(E_0^2)_{0.1}\left(\frac{\omega_9}{0.1}\right)^{7/2},$$

$$\frac{V_0^2}{c^2}=\left(\frac{V_0^2}{c^2}\right)_{0.1}\left(\frac{\omega_9}{0.1}\right)^{3/2},\qquad \omega_0\simeq2\omega_p.$$

$\omega_p=\omega_9\times5\times10^9$ Hz, and R_0 is the distance between the disc-plasma and the homogeneous synchrotron self-absorbed source. The density variation in accretion discs has been discussed by Rees (1984). Let us take

$$n=n_0(r/r_0)^{-\beta} \tag{10}$$

where n is the density at a reference point r_0. Typical values are $n_0=10^{17}\ \mathrm{m^{-3}}$ at $r_0=1.5\times10^{11}M_8$ m, where M_8 is the black hole mass in units of $10^8 M_\odot$. One realizes that the size of the scattering region varies with the frequency of the incident radiation. Equation (10) can be inverted in order to express r as a function of the plasma frequency:

$$r^2 = r_0^2 \left(\frac{\omega_9}{0.1}\right)^{-4/\beta}. \tag{11}$$

Substituting equations (9) and (11) in equation (8) one obtains for the spectral shape of the scattered radiation:

$$F_s = \frac{m^2 c^3}{64 e^2}\, r_0^2\, \frac{5\times 10^9}{(x^4)_{0.1}} \left(\frac{\omega_9}{0.1}\right)^{1.22-4/\beta}. \tag{12}$$

One notes that the spectral shape of the scattered radiation is very different from that of the self-absorbed synchrotron radiation. The spectral index $\alpha_s = 1.22 - 4/\beta$ is intimately related to the electron density variation in the disc. For radiation-pressure-supported tori, Rees (1984) argues that $\beta \geqslant 3$. If the Raman scattering takes place in such discs, the spectral index $\alpha_s \geqslant 1.22 - \frac{4}{3} = -0.11$. If the scattering occurs in ion-pressure-supported discs for which $\beta = +3/2$, one finds $\alpha_s = 1.22 - \frac{8}{3} = -1.4$, which is far from the observed spectrum. Thus, scattering in radiation-pressure-supported tori seems to account rather well for the observed radio spectrum of the self-absorbed synchrotron sources. To fix the value of r_0^2, we assume that there is no transmission of the incident radiation and all we receive is the scattered radiation. In this case, half of the incident energy goes to the electron plasma wave and the other half to the scattered wave. Therefore

$$F_s(\omega_9 = 0.1) \simeq \frac{F_0(\omega_9 = 0.2)}{2},$$

which gives

$$r_0^2 = 6.5 \times 10^{27}\ \mathrm{m}^2$$

and

$$F_S(\omega_9) = 1.61 \times 10^{26} (\omega_9/0.1)^{1.22-4/\beta}\ \mathrm{W\ Hz}^{-1}$$

where, for comparison,

$$F_0(0.1) = 5.7 \times 10^{25}\ \mathrm{W\ Hz}^{-1}. \tag{13}$$

The geometry of radiation-supported thick discs or tori, with their deep funnels and extensive size (10^2–10^4 times the Schwarzschild radius, e.g. Paczynski & Wiita 1980), implies that if the original emission occurs on a scale $\leqslant r_0$ then a very large fraction of this radiation will probably be intercepted by the thick accretion disc. Only if the incident radiation is strongly beamed along the funnel axes (e.g. Königl 1987) would the percentage of scattered radiation become small. Geometrically thick, ion-supported discs would also intercept the bulk of the emitted flux, but their lower densities (Rees *et al.* 1982), as well as their lower values of β, indicate that they are not likely to support this type of Raman scattering to any significant extent. Because geometrically thin accretion discs are believed to flare at large radii, even they can intercept a significant fraction of isotropically emitted radiation, and so this Raman reprocessing may be important for them as well. However, details of the ratio of scattered versus directly observed emission are strongly model-dependent and will be postponed until a subsequent paper.

Finally, one must check if the threshold condition equation (3) is satisfied or not. For Raman scattering $K_p \lambda_D \ll 1$ initially, and therefore equation (3) reduces to

$$(V_0/c)^2 \geqslant 4\nu_c^2/\omega_p^2,$$

where

$\nu_c = 1.4\times10^4 n_{16} T_5^{-3/2}\ \mathrm{s}^{-1}$

$n = n_{16}\times10^{16}\ \mathrm{m}^{-3}, \qquad T_e = 10^5 T_5\ \mathrm{K}.$

Now

$$\frac{V_0^2}{c^2} = \frac{e^2 E_0^2}{m_e^2 \omega_0^2 c^2} = \frac{9.42\times10^{-13} L_{34}}{R_{pc}^2 n_{16}}$$

where $L = L_{34}\times10^{34}$ W, $R_0 = R_{pc}\times3\times10^{16}$ m, and $\omega_0 \simeq 2\omega_p$. The threshold condition becomes

$$\frac{L_{34}}{R_{pc}^2} \geqslant 27.74\, n_{16}^2 T_5^{-3}$$

and is easily satisfied since $R_{pc} \ll 1$. The incoherence of the incident field effectively reduces the luminosity L. The threshold condition remains satisfied even when L is reduced to 1 per cent of its initial value.

3 Conclusions

Incident radiation with flux density $F_0 \propto \omega_0^{5/2}$ undergoes Raman scattering in a medium with electron plasma frequency $\omega_0/2$ and emerges with a scattered flux density $F_s \propto \omega^{1.22-4/\beta}$. The scattered component at $\omega_0/2$ may not undergo second Raman scattering in a region of electron plasma frequency $\omega_0/4$ because, in the first Raman scattering, half the incident energy goes to the electron plasma wave which heats the electrons and thus the threshold for Raman scattering (equation 3) is raised. It is therefore distinctly possible that the radio emission typically observed with a spectral index between 0.3 and 0.5 has a large component due to Raman scattering. The electron density variation in the accretion disc is intimately linked with the spectral index of the scattered radiation. Raman scattering not only modifies the radiation spectrum, but in so doing also heats the plasma. This anomalous radio heating of the emission-line regions is discussed by Krishan (1987).

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References

Figueroa, H., Joshi, C., Azechi, H., Ebrahim, N. A. & Estabrook, K., 1984. *Phys. Fluids,* **27,** 1887.
Hasegawa, A., 1978. *Bell Syst. tech. J.,* **57,** 3069.
Königl, A., 1981. *Astrophys. J.,* **243,** 700.
Krishan, V., 1983. *Astrophys. Lett.,* **23,** 133.
Krishan, V., 1987. *Mon. Not. R. astr. Soc.,* **226,** 629.
Krishan, V. & Wiita, P. J., 1986. In: *Quasars,* p. 319, eds Swarup, G. & Kapahi, V. K., Reidel, Dordrecht, Holland.
Liu, C. S. & Kaw, P. K., 1976. In: *Advances in Plasma Physics,* p. 83, Vol. 6, eds Simon, A. & Thompson, W. B., Wiley, New York.
Paczynski, B. & Wiita, P. J., 1980. *Astr. Astrophys.,* **88,** 23.
Rees, M. J., 1984. *Ann. Rev. Astr. Astrophys.,* **22,** 471.
Rees, M. J., Begelman, M. C., Blandford, R. D. & Phinney, E. S., 1982. *Nature,* **295,** 17.
Spangler, S. R., 1982. In: *Extragalactic Radio Sources,* p. 297, eds Heeschen, D. S. & Wade, C. M., Reidel, Dordrecht, Holland.