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Scattering of quasar radiation in intercloud plasma

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Summary. Three different levels of description are available to describe the interaction of electromagnetic radiation with electrons in a fully ionized plasma: when the scattering of radiation occurs by excitation of a plasmon, the collective plasma oscillation of the electrons, it is called stimulated Raman scattering; if it occurs by excitation of a heavily damped plasmon, it is called stimulated Compton scattering, and if it occurs by excitation of individual electrons, it is called Compton scattering. The scattering rates in each case differ significantly. The physics of these mechanisms is illustrated by taking a quasar as the source of intense radiation and the hot plasma surrounding it as the scattering medium. It is concluded that, through Raman scattering, the non-thermal radio radiation equilibrates with the intercloud medium at much higher temperatures than are achievable through Compton processes.

1 Introduction

The broad emission-line regions of quasars consist of high-density ($n \approx 10^{10}$–10^{11} cm^{-3}) and low-temperature (10^4–10^5 K) clouds confined by a low-density ($n \approx 10^4$ cm^{-3}) and high-temperature ($T \sim 10^8$ K) intercloud medium. The intercloud medium is efficiently heated to such temperatures by Compton scattering of the high-frequency non-thermal radiation of the quasars (Levich & Sunyaev 1971; Perry & Dyson 1985). If Compton heating is the main mechanism, then the clouds can be in pressure equilibrium with the intercloud medium over a small range of pressures in the neighbourhood of $(nT) \sim 10^{12}$–10^{14} K cm^{-3}. The need for additional heating processes is evident. First, the range of equilibrium pressures needs to be extended. Secondly, the intercloud medium exerts a drag force on the moving clouds and the drag-limited speed is found to be too small for $T \sim 10^8$ K to account for the observed line-widths. Thirdly, a higher intercloud temperature can lead to a simpler motion of the clouds, as is indicated by the uniformity and simplicity of the line profiles observed in quasars and Seyferts. These points have been discussed by Mathews & Capriotti (1985) in a very lucid manner. Additional heating by cloud motions and cosmic rays has been suggested by Mathews (1974) and Krolik, McKee & Tarter (1981).

The aim of this paper is to point out that the physics of the scattering processes depends upon the properties of the radiation and of the scattering medium. The interaction of an intense electromagnetic radiation in a plasma is very different from one of weak intensity. A strong electromagnetic wave excites electron plasma oscillations in a plasma. In such a case the scattering is a three-wave process and is called stimulated Raman scattering. The scattering rate is found to be larger by several orders of magnitude than scattering by individual electrons. Another interesting case appears when the excited electron plasma wave has a wave vector greater than or equal to the Debye wave vector. In this case the electron plasma wave suffers heavy Landau damping and the wave loses its collective nature. The scattering is now by the shielded electrons or by the electrons with their Debye cloud. This is known as scattering by resistive quasi-modes, and in plasma physics literature it is identified with stimulated Compton scattering. The scattering by individual bare electrons as discussed by Levich & Sunyaev (1971) is called Compton scattering. In the next sections the scattering rate for these three processes are calculated for the case of quasar radiation and the intercloud medium. It is shown that the intercloud medium can attain a much higher temperature via stimulated Raman scattering of the radio radiation.

2 Stimulated Raman scattering in the intercloud medium

Consider a large-amplitude plane-polarized electromagnetic pump wave $\mathbf{E}_0=2E_0\hat{\mathbf{e}}_0\cos(\mathbf{K}_0\mathbf{x}-\omega_0 t)$ propagating in a plasma of electron density n and temperature T. Stimulated Raman scattering takes place when the incident photon $(\omega_0, \mathbf{K}_0)$ decays into a scattered photon $(\omega_s, \mathbf{K}_s)$ and an electron plasma wave $(\omega_e, \mathbf{K}_e)$ such that

$$\omega_0=\omega_s+\omega_e \quad \text{and} \quad \mathbf{K}_0=\mathbf{K}_s+\mathbf{K}_e. \tag{1}$$

The equilibrium consists of electrons oscillating with velocity $V_0=eE_0/m\omega_0$ in the field of the incident wave. Ions form a stationary background. One can study the time development of this equilibrium by perturbing it. Let a propagating density perturbation (ω, k) associated with an electrostatic wave disturb the equilibrium. The electron density fluctuations will be produced by the oscillating field E_0 and lead to currents at $(\omega\pm l\omega_0, \mathbf{K}\pm l\mathbf{K}_0)$ where l is an integer; the lowest order coupling corresponds to $l=1$. These currents generate mixed electromagnetic–electrostatic side-band modes at $(\omega\pm l\omega_0, \mathbf{K}\pm l\mathbf{K}_0)$. The side-band modes, in turn, interact with the pump wave field producing a ponderomotive bunching force ∇E^2 which amplifies the original density perturbation. Thus there is a positive feed-back which will lead to instability of the original density perturbation and the side-band modes if the rate of transfer of energy into them exceeds their natural damping rates. This makes it a threshold-dependent phenomenon. The necessary mathematical details of this process are given by Liu & Kaw (1976) and Drake *et al.* (1974). The dispersion relation describing stimulated Raman scattering is (Drake *et al.* 1974)

$$(\omega-\omega_e+i\Gamma_p)(\omega-\omega_e+i\Gamma_-)=-\frac{V_0^2}{c^2}\psi^2\omega_0\omega_p, \tag{2}$$

where

$$\Gamma_p=\frac{\sqrt{\pi}}{2}\frac{\omega_p}{K_e^3\lambda_D^3}\exp\left(-\frac{1}{2K_e^3\lambda_D^2}-\frac{3}{4}\right)+\gamma_{ei},$$

$$\gamma_{ei}=(3\omega_p)/(4\pi n\lambda_D^3). \tag{3}$$

Γ_p is the damping rate of the electron plasma wave; γ_{ei} is the electron–ion collision frequency, $\Gamma_-=\omega_p^2\gamma_{ei}/2\omega_s^2$ is the collisional damping rate of the electromagnetic wave, $\omega_p=(4\pi ne^2/m)^{1/2}$ is the electron plasma frequency, $\psi=|\sin\phi|\cos\theta$, θ is the angle between $\mathbf{K}_e$ and $\mathbf{K}_0$ and $\Phi=\pi/2$ when the two electromagnetic waves are polarized in the same direction; and λ_D is the Debye wavelength. For stimulated Raman scattering, one finds the growth rate γ_{SR} from equation (2) by setting $\omega=\omega_l+i\gamma_{SR}$:

$$\gamma_{SR}=-\tfrac{1}{2}(\Gamma_p+\Gamma_-)\pm\tfrac{1}{2}[(\Gamma_p-\Gamma_-)^2+4(V_0^2/c^2)\psi^2\omega_0\omega_p]^{1/2}. \tag{4}$$

The threshold power $(V_{0T}/c)_{SR}$ is obtained by setting $\gamma_{SR}=0$:

$$\left(\frac{V_{0T}}{c}\right)^2_{SR}=\frac{1}{\psi^2}\left(\frac{\Gamma_p}{\omega_p}\right)\left(\frac{\Gamma_-}{\omega_0}\right). \tag{5}$$

The maximum growth rate for $\omega_p\gg\gamma_{SR}\gg\Gamma_p$ is found to be

$$\gamma_{SR}=\frac{V_0}{c}\,\psi(\omega_0\omega_p)^{1/2} \tag{6}$$

for $(V_0/c)_{SR}>\Gamma_p/(\psi\omega_0\omega_p)^{1/2}$. In the above analysis $\omega_0\gg\omega_l\simeq\omega_p$ and therefore, $\omega_0\simeq\omega_s$, $\omega_0=K_0c$, $K_e=2K_0\cos\theta$, and for stimulated Raman scattering $K_e\lambda_D\ll1$ so that the electron plasma wave is only weakly damped.

In the intercloud medium, we choose the typical values of the parameters as

$$E_0^2=\frac{L}{R^2}=\frac{0.37\,L_{47}}{r_{pc}^2}.$$

Here $L=L_{47}\times10^{47}\,\mathrm{erg\,s^{-1}}$ is the luminosity of the quasar radiation and $R=r_{pc}\times3\times10^{18}\,\mathrm{cm}$ is the position of the intercloud medium of electron density $n=n_4\times10^4\,\mathrm{cm^{-3}}$ and temperature $T=T_8\times10^8\,\mathrm{K}$. The threshold condition $(V_0/c)^2_{SR}\geq(V_{0T}/c)^2_{SR}$ translates to

$$\frac{L_{47}}{r_{pc}^2}\geq\frac{2.85\times10^{-8}n_4^{1/2}}{\cos^2\theta T_8^{3}}\left[\frac{26.72\times10^{20}n_4^3}{\omega_0^3\cos^3\theta}\exp\left(-\frac{1.19\times10^{14}n_4}{\omega_0^2\cos^2\theta T_8}-\frac{3}{4}\right)+2.31\times10^{-14}n_4^2\right]. \tag{7}$$

The condition $K_e\lambda_D\ll1$ and $\omega_0\simeq K_0c\gg\omega_p$ translates to

$$5.46\times10^6n_4^{1/2}\ll\omega_0<\frac{1.54\times10^7}{\cos\theta}\,n_4^{1/2}T_8^{-1/2}. \tag{8}$$

One observes that $\cos\theta\ll1$ is required for ω_0 to be large enough to have significant luminosity. One finds that, for $\cos\theta=10^{-2}$,

$$\left(\frac{L_{47}}{r_{pc}^2}\right)_{SR}\geq\frac{2.85\times10^{-4}n_4^{1/2}}{T_8^3}\left[\frac{26.72\times10^{14}n_4^3}{\omega_0^3}\exp\left(-\frac{1.19\times10^{18}n_4}{\omega_0^2T_8}-\frac{3}{4}\right)+2.31\times10^{-14}n_4^2\right], \tag{9}$$

$$\gamma_{SR}=2.274\times10^8\left(\frac{L_{47}}{r_{pc}^2}\right)^{1/2}\left(\frac{n_4^{1/2}}{\omega_0}\right)^{1/2}, \tag{10}$$

and

$$5.46\times10^6n_4^{1/2}\ll\omega_0\ll1.54\times10^9n_4^{1/2}T_8^{-1/2}. \tag{11}$$

The temperature at which the intercloud medium attains equilibrium with the quasar radiation is given by the equality in equation (7). It is known that the maximum value of $(K_e\lambda_D)=0.4$, such that the Langmuir wave retains its identity and the analysis of stimulated Raman scattering remains valid. The relation $(K_e\lambda_D)=0.4$ gives

$$\left(\frac{\omega_0\cos\theta T_8^{1/2}}{n_4^{1/2}}\right)_{max}=6.17\times10^6$$

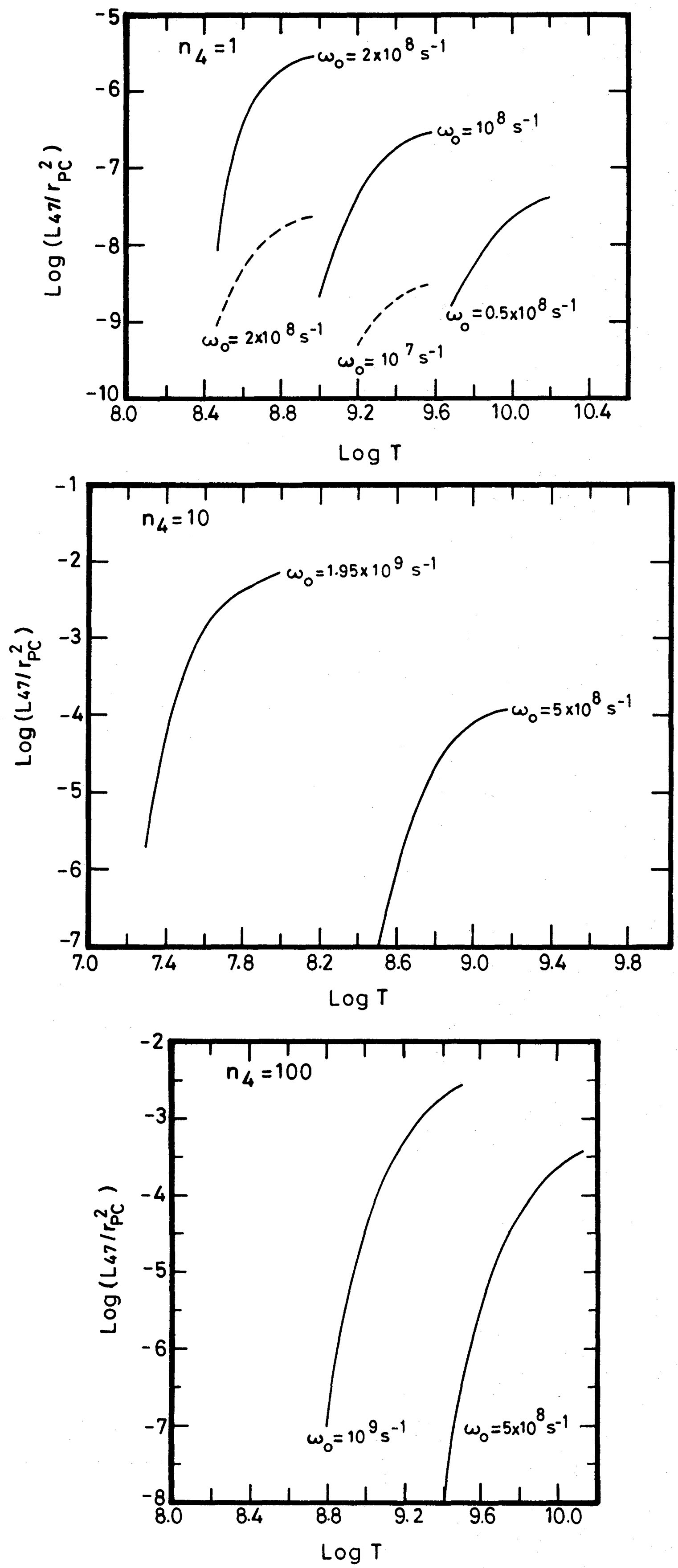

Figure 1. Variation of threshold radiation flux and frequency with the temperature of plasma for stimulated Raman scattering, (a) for $n_4=1$, (b) for $n_4=10$ and (c) for $n_4=100$.

and, for $\cos\theta=10^{-2}$,

$$\left(\frac{\omega_0 T_8^{1/2}}{n_4^{1/2}}\right)_{\max}=6.17\times10^8. \tag{12}$$

We calculate the equilibrium temperature from equation (7) for several values of $(L_{47}/r_{\rm pc}^2)_{\rm SR}$, ω_0, n_4 honouring equation (12). The results are plotted in Fig. 1(a)–(c). These plots show that temperatures much higher than 10^8 K can be attained by the right choice of incident radiation with reasonable luminosity for a given density n. The dashed curves in Fig. 1(a) are for $\cos\theta=10^{-1}$.

3 Stimulated Compton scattering

Stimulated Raman scattering changes to stimulated Compton scattering when the electron plasma wave w_l is heavily damped, which is expressed by the condition

$$K_e\lambda_D \gg 1$$

or

$$\omega_0 \gg \frac{1.54\times10^7}{\cos\theta}\, n_4^{1/2} T_8^{-1/2} \tag{13}$$

and also $\omega_0 \gg 5.46\times10^6 n_4^{1/2}$ as before. The threshold in this case is given by (Drake *et al.* 1974)

$$\left(\frac{V_{0T}}{c}\right)^2_{\rm SC}=2\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{\Gamma_-}{\omega_0}\right)\exp\left(\frac{1}{2}\right)(K_0\lambda_D)^2$$

$$=\frac{6.12\times10^{-9}}{\omega_0}\, n_4 T_8^{-1/2}. \tag{14}$$

Therefore the condition for stimulated Compton scattering to occur is

$$\left(\frac{V_0}{c}\right)^2_{\rm SC}=10^{14}\frac{L_{47}}{r_{\rm pc}^2}\frac{1}{\omega_0^2} \geq \frac{6.12\times10^{-9}}{\omega_0}\, n_4 T_8^{-1/2}$$

or

$$\left(\frac{L_{47}}{r_{\rm pc}^2}\right)_{\rm SC} \geq 6.12\times10^{-23}\omega_0 n_4 T_8^{-1/2}. \tag{15}$$

The growth rate $\gamma_{\rm SC}$ is given by

$$\gamma_{\rm SC}=\frac{\omega_0}{2}\frac{V_0^2}{c^2}\sqrt{\frac{\pi}{2}}\exp\left(-\frac{1}{2}\right)(K_0\lambda_D)^{-2}-\Gamma_-$$

$$=\frac{3.44\times10^{28}}{\omega_0^3}\left(\frac{L_{47}}{r_{\rm pc}^2}\right)\frac{n_4}{T_8}-\frac{4.4\times10^6}{\omega_0^2}\, n_4^2 T_8^{-3/2}. \tag{16}$$

In order to compare the growth rates for stimulated Raman and Compton scatterings, we present the results in Tables 1 and 2. $\gamma_{\rm SR}$ is calculated for $(L_{47}/r_{\rm pc}^2)=9(L_{47}/r_{\rm pc}^2)^{\rm SR}_{\rm Th}$. $\gamma_{\rm SC}$ is calculated for $(L_{47}/r_{\rm pc}^2)=10^{-6}$. This is done to illustrate that stimulated Raman scattering occurs at a much faster rate, $\gamma_{\rm SR}$, than the stimulated Compton scattering ($\gamma_{\rm SC}$), which is again much larger than the Compton scattering rate $\gamma_{\rm C}=(4\sigma_{\rm T}\varepsilon/mc)$ of isotropic radiation by bare electrons, where $\sigma_{\rm T}$ is the Thomson cross-section and ε the energy density of the incident radiation.

Table 1. Growth rates for stimulated Raman scattering.

$n_4=1$

T_8	ω_0	$(L_{47}/r^2_{pc})^{SR}_{Th}$	γ_{SR} for $L_{47}/r^2_{pc}=9(L_{47}/r^2_{pc})^{SR}_{Th}$	$\omega_0 \gg 5.4\times10^6$ $(\omega_0 T_8^{1/2})_{max}=0.617\times10^9$
1	6.17×10^8	6.71×10^{-5}	2.25×10^2	
	5×10^8	2.46×10^{-5}	1.51×10^2	
	4×10^8	3.3×10^{-6}	6.20×10^1	
	3×10^8	2.4×10^{-7}	1.93×10^1	
10	1.95×10^8	2.12×10^{-6}	7.11×10^1	
	1×10^8	2.42×10^{-9}	3.35	

$n_4=10$

T_8	ω_0	$(L_{47}/r^2_{pc})^{SR}_{Th}$	γ_{SR} for $L_{47}/r^2_{pc}=9(L_{47}/r^2_{pc})^{SR}_{Th}$	$\omega_0 \gg 1.73\times10^7$ $(\omega_0 T_8^{1/2})_{max}=1.95\times10^9$
1	1.95×10^9	6.7×10^{-3}	2.24×10^3	
0.6	1.95×10^9	3.8×10^{-3}	1.69×10^3	
0.5	1.95×10^9	2.34×10^{-3}	1.32×10^3	
0.3	1.95×10^9	1.69×10^{-4}	3.57×10^2	
15	5×10^8	1.13×10^{-4}	5.75×10^2	
12	5×10^8	9.97×10^{-5}	5.41×10^2	
10	5×10^8	7.79×10^{-5}	4.78×10^2	
8	5×10^8	4.63×10^{-5}	3.68×10^2	
5	5×10^8	5.34×10^{-6}	1.25×10^2	

$n_4=100$

T_8	ω_0	$(L_{47}/r^2_{pc})^{SR}_{Th}$	γ_{SR} for $L_{47}/r^2_{pc}=9(L_{47}/r^2_{pc})^{SR}_{Th}$	$\omega_0 \gg 5.47\times10^7$ $(\omega_0 T_8^{1/2})_{max}=6.17\times10^9$
35	10^9	2.82×10^{-3}	3.62×10^3	
30		2.52×10^{-3}	3.42×10^3	
25		1.99×10^{-3}	3.04×10^3	
20		1.19×10^{-3}	2.35×10^3	
10		2.45×10^{-5}	3.37×10^2	
150	5×10^8	3.57×10^{-4}	1.82×10^3	
100		2.46×10^{-4}	1.51×10^3	
75		1.2×10^{-4}	1.05×10^3	
50		1.7×10^{-5}	0.39×10^3	
25		9.91×10^{-9}	9.5	

Table 2. Growth rates for stimulated Compton scattering.

$n_4=1$

T_8	ω_0	$(L_{47}/r^2_{pc})^{SC}_{Th}$	γ_{SC} for $L_{47}/r^2_{pc}=10^{-6}$	$(\omega_0 T_8^{1/2})_{min}=0.617\times10^9$
1	10^9	1.29×10^{-13}	3.44×10^{-5}	
	10^{10}	1.29×10^{-12}	3.44×10^{-8}	
	10^{11}	1.29×10^{-11}	3.44×10^{-11}	
10	10^9	0.4×10^{-13}	1.24×10^{-6}	
	10^{10}	0.4×10^{-12}	1.24×10^{-9}	

$\gamma_C=3.4\times10^{-10}(L_{47})/r^2_{pc}$.
$(\gamma_C)_{max}\simeq3.4\times10^{-10}$.

4 Discussion and conclusion

The main characteristics of stimulated Raman scattering are: (i) the electromagnetic radiation is scattered off the electron plasma wave, satisfying the phase-matching conditions (equation 1) for this three-wave interaction; (ii) it is a threshold process, the threshold (equation 7) depending on the energy density of the incident radiation, the electron density and the temperature of the plasma; (iii) the scattering rate γ_{SR} is larger by orders of magnitude than the Compton scattering processes; (iv) in deriving the scattering rate, the incident radiation has been assumed to be of coherent nature, which may not be true in the case of quasars. Now, for a spectral index of -1, i.e. $L(\omega_0)/\omega_0 \propto \omega_0^{-1}$, the luminosity $L(\omega_0)$ is same at all frequencies. The effect of the incoherence introduced by the finite bandwidth and small polarization is to reduce the effective energy density of the incident radiation available for the scattering process. This point has been discussed in detail by Krishan (1987). In any case one can see from Fig. 1 that it is possible to satisfy the threshold condition. The process occurs for a specific range of frequencies (equation 11).

In stimulated Compton scattering the incident radiation is scattered by the heavily damped electron plasma wave ($K_e\lambda_D \gg 1$). The threshold condition (equation 15) is more easily satisfied. The scattering rate γ_{SC} is much smaller than γ_{SR}, but it is still much larger than γ_C which is the scattering rate when the isotropic radiation is scattered by individual electrons. It is simple to show that

$$\gamma_{SC} = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\right)\left(\frac{\sigma_T \varepsilon}{mc}\right)\left(\frac{n\lambda_D^3}{K_B T/mc^2}\right),$$

which indicates that scattering depends on the number of electrons in a wavelength cube ($n\lambda_D^3$). This is due to the fact that one cannot consider thermal electrons in a plasma to be free when one is dealing with the scattering of low-frequency waves. In a volume of size λ_D^3, there are always many plasma electrons. The waves with wavelength much less than the interelectron distance will force each electron to oscillate independently of all others, whereas a low-frequency wave can make many electrons oscillate coherently. Therefore the scattering occurs by fluctuations in the electron density and the fluctuations are in turn caused by the motion of thermal particles in the plasma itself (Kaplan & Tsytovich 1973). These additional effects of electron density and temperature are seen in the expression for γ_{SC}.

In conclusion, depending upon the frequency and the energy density of the incident radiation and the electron density and the temperature of the plasma, one or more of the three scattering processes may be in action. The intercloud medium can be heated to temperatures higher than 10^8 K through stimulated Raman scattering of the non-thermal radio radiation.

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