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Anomalous heating of quasar emission-line regions

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Summary. It is shown that the non-thermal radio radiation from a quasar is intense enough to drive parametric instabilities in the fully ionized emission-line regions. These instabilities cause significant enhancement of the plasma resistivity around the normal modes of the plasma and thus lead to an anomalous heating effect. The maximum plasma temperature is a function of the luminosity of the non-thermal radio radiation and the plasma parameters of the emission-line regions.

1 Introduction

The ultraviolet continuum of a quasar photoionizes its emission-line regions. The electron density in these regions varies from 10^8 to 10^{10} cm^{-3} and the electron temperature is of the order of 10^4 K. In addition to the relatively cool photoionized regions, less dense and hotter regions are also expected to be present and additional heating processes may be operative in these regions. Davidson & Netzer (1979) have reviewed some of the additional heating processes proposed by several workers. Osterbrock & Parker (1965) and Eilek & Caroff (1976) have proposed that energetic non-thermal charged particles could cause excitations and heating. Nussbaumer & Osterbrock (1970) have held cloud–cloud collisions to be responsible for producing ionizing radiation.

Daltabuit & Cox (1972), Daltabuit, MacAlpine & Cox (1978), and Davidson (1972) have considered several consequences of the cloud–cloud collisions, like shocks, compression and heating. Krolik, McKee & Tarter (1978) have pointed out that radio frequency waves can heat the gas through free–free absorption processes. It is known that when the frequency of the incident radiation is close to the electron plasma frequency of the absorbing plasma, the radiation energy preferentially goes to the electron plasma oscillations which can become unstable and grow to a large amplitude. These electrostatic plasma waves then undergo damping which may be collisional or collisionless landau damping, heating the electrons in the process (DuBois & Goldman 1965; Kaw & Dawson 1969). In this paper, we consider the parametric decay of radio waves with frequency near the electron plasma frequency of the emission-line regions. The radio wave decays into an electron plasma wave and an ion acoustic wave leading to the anomalous absorption of the radio waves.

2 Parametric decay instability

The parametric decay of the radio waves can be described as:

$$\omega_0=\omega_e+\omega_i; \quad \mathbf{K}_0=\mathbf{K}_e+\mathbf{K}_i, \tag{1}$$

where $(\omega_0, \mathbf{K}_0)$ is the frequency and wave vector of the incident radiation,

$$\omega_0^2=\omega_{\varrho e}^2+K_0^2c^2, \quad \omega_e^2=\omega_{\varrho e}^2+3K^2V_e^2,$$

$$\omega_{\varrho e}^2=\frac{4\pi ne^2}{m_e}, \quad \omega_i=\omega_{pi}[1+(K\lambda_D)^{-2}]^{-1/2},$$

$$\omega_{\varrho i}^2=\frac{4\pi ne^2}{m_i}, \quad \lambda_D=\frac{V_e}{\omega_{\varrho e}},$$

Since $\omega_0\simeq\omega_{\varrho e}$, $K_0\simeq 0$ and $|\mathbf{K}|=|\mathbf{K}_e|=|\mathbf{K}_i|$, where n is the electron density, V_e is the electron thermal velocity, m_e and m_i are the electron and proton masses. The dispersion relation for the decay instability is given as (Liu & Kaw 1976):

$$(\omega^2+2i\omega\Gamma_a-K^2C_s^2)(\omega-\Delta+i\Gamma_\varrho)+\frac{(K\cdot V_0)^2}{2\omega_{\varrho e}}\omega_{\varrho i}^2=0, \tag{2}$$

where $\Delta=\omega_0-\omega_e$; ω is the frequency of the decaying electrostatic wave in the presence of the pump wave of frequency ω_0; Γ_ϱ is the damping rate of the electron plasma wave given by

$$\Gamma_\varrho=\frac{\sqrt{\pi}\,\omega_{\varrho e}}{2K^3\lambda_D^3}\exp\left(-\frac{1}{2K^2\lambda_D^2}-\frac{3}{4}\right)+\nu_{ei},$$

ν_{ei} is the electron–ion collision frequency,

$$\Gamma_a=\left(\frac{\pi}{8}\right)^{1/2}KC_s\left(\frac{m_e}{m_i}\right)^{1/2}\left(\frac{T_e}{T_i}\right)^{3/2}\exp\left[-\frac{1}{2}\left(3+\frac{T_e}{T_i}\right)\right]$$

is the damping rate of the ion wave, $C_s=(T_e/m_i)^{1/2}$ is the ion sound speed, T_e is the electron temperature, T_i is the ion temperature, $V_0=(eE_0/m_e\omega_0)$ is the quiver velocity of an electron in the electric field E_0 of the radio wave. One solves equation (2) for complex roots such that $K\lambda_D\ll 1$, $\omega\sim\omega_i\sim KC_s$. Let $\omega=KC_s+i\delta$, $\delta\ll KC_s$. Solving equation (2) one finds the growth rate $\gamma=\mathrm{Re}\,\delta$ as

$$\gamma=-\frac{(\Gamma_\varrho+\Gamma_a)}{2}+\mathrm{Re}\left[\frac{(K\cdot V_0)^2}{4KC_s}\sqrt{\frac{m_e}{m_i}}\,\omega_{\varrho i}+\frac{(\Gamma_a-\Gamma_\varrho-i\Delta)^2}{4}+\frac{i\Gamma_\varrho\Delta}{2}\right]^{1/2}. \tag{3}$$

Here γ is the growth rate of both the decay waves ω_e and ω_i. We know that parametric excitation is a threshold process and the threshold can be found by setting $\gamma=0$ in equation (3). The threshold is given as:

$$\frac{(K\cdot V_0)^2}{4KC_s}\omega_{\varrho i}\left(\frac{m_e}{m_i}\right)^{1/2}=\Gamma_a\Gamma_\varrho. \tag{4}$$

Equation (4) describes the minimum value of the electric field E_0 or the quiver velocity V_0 required such that the rate at which the energy is being fed into the electron plasma and ion acoustic waves equals their rate of damping. For the parametric process to occur, the field E_0 must exceed the value given by equation (4). One must check whether this condition is satisfied in the case of quasars and their associated emission-line regions. After growing for sometime, the instability will be shut off because the electrons and ions get trapped in the electric fields of the electron plasma and ion sound waves, their temperature increases and so do the damping rates Γ_a and Γ_ϱ. The effective maximum collision frequency or the damping rate one can hope to get before the instability is shut-off is also given by equation (4) as

$$\Gamma_a \Gamma_\varrho |_{\max} = \frac{(K \cdot V_0)^2}{4KC_s} \omega_{\varrho i} \left(\frac{m_e}{m_i} \right)^{1/2}. \tag{5}$$

Now, the electron temperature T_e can be greater than or equal to the ion temperature T_i because electrons are generally the first ones to get heated in any heating process. The ion wave damping rate Γ_a is smaller for $T_e > T_i$ then for $T_e = T_i$ and therefore the threshold condition equation (4) is more easily satisfied for $T_e > T_i$. Here for numerical estimates, we take $T_e = T_i$. In order to satisfy equation (4) initially, one must have $K\lambda_D \ll 1$ so that Γ_ϱ and Γ_a are small. V_0 can be expressed in terms of the radio luminosity, L, and the distance of the emission-line region, r, from the central source of radio radiation. Now

$$\frac{V_0^2}{c^2} = \frac{e^2 E_0^2}{m_e^2 \omega_0^2 c^2} = \frac{10^8 L_{41}}{\gamma_{pc}^2 \omega_0^2} \simeq \frac{10^8 L_{41}}{\gamma_{pc}^2 \omega_{\varrho e}^2} = \frac{10^{-9}}{3} \frac{L_{41}}{\gamma_{pc}^2 n_8}$$

where $L = L_{41} \times 10^{41}$ erg s^{-1}, $n = n_8 \times 10^8$ cm^{-3}, $r = 3 \times 10^{18} \gamma_{pc}$ cm, $T = T_4 \times 10^4$ K.

Equation (4) can be written as:

$$\frac{(K\lambda_D)}{4} \frac{V_0^2}{c^2} \frac{c^2}{\lambda_D^2} \left(\frac{m_e}{m_i} \right)^{1/2} \geqslant (\Gamma_\varrho^2)_{\text{eff}} = (\Gamma_\varrho \Gamma_a) \tag{6}$$

or

$$(K\lambda_D) \times \frac{3.86 \times 10^{11} L_{41}}{\gamma_{pc}^2 T_4} \geqslant (\Gamma_\varrho^2)_{\text{eff}}.$$

We find for $K\lambda_D = 0.11$, $\Gamma_\varrho = \nu_{ei} = 4.4 \times 10^3 n_8 T_4^{-3/2}$. Thus at this value of $K\lambda_D$, equation (6) is easily satisfied. As the instability progresses, the electrons and ions get heated and the damping rate $(\Gamma_\varrho)_{\text{eff}}$ increases. One can invert equation (6) to find the maximum value of the damping rate at which the instability is shut-off. The maximum value of the anomalous absorption rate γ_{an} is given as:

$$\gamma_{an} = \frac{[(\Gamma_a \Gamma_\varrho)_{\max}]^{1/2}}{c} \simeq \frac{(3.86 \times 10^{11})^{1/2}}{3 \times 10^{10}} \left(\frac{L_{41}}{T_4 \gamma_{pc}^2} K\lambda_D \right)^{1/2} \simeq 2 \times 10^{-5} \left(\frac{L_{41} K\lambda_D}{T_4 \gamma_{pc}^2} \right)^{1/2}. \tag{7}$$

This is much larger than the free–free absorption rate $\nu_{ei}/C = 1.4 \times 10^{-7} n_8 T_4^{-3/2}$ cm^{-1}. One can calculate the maximum value, the electron temperature can have through the decay instability by equating $(\Gamma_\varrho \Gamma_a)_{\max}$ to the Landau damping rate and solving for the effective maximum value of $(K\lambda_D)_{\max}$ or the electron temperature. One finds from:

$$(\Gamma_a \Gamma_\varrho)_{\max} = \frac{(3.86 \times 10^{11}) L_{41} (K\lambda_D)_{\max}}{T_4 \gamma_{pc}^2}$$

$$= \left\{ \frac{\sqrt{n}\, \omega_{\varrho e}}{2(K^3 \lambda_D^3)_{\max}} \exp \left[-\frac{1}{2(K^2 \lambda_D^2)_{\max}} - \frac{3}{4} \right] \right\}$$

$$\times \left[(K\lambda_D)_{\max} \exp(-2) \frac{m_e}{m_i} \omega_{\varrho e} \right] \tag{8}$$

that

$$(K\lambda_{\mathrm{D}})_{\max}=0.26$$

for

$$\frac{L_{41}}{T_4\gamma_{\mathrm{pc}}^2 n_8^{1/2}}\simeq 1.$$

Thus an increase of $K\lambda_{\mathrm{D}}$ from 0.11 to 0.26 leads to an increase of electron temperature from 10^4 to 5.5×10^4 K since

$$\frac{(K\lambda_{\mathrm{D}})_{\max}}{(K\lambda_{\mathrm{D}})_{\min}}=\frac{0.26}{0.11}=\left(\frac{T_{\mathrm{e\,max}}}{T_{\mathrm{e\,min}}}\right)^{1/2}.$$

3 Incoherence of the incident field

The above results have been derived assuming the incident field to be a perfectly coherent field. In reality, some amount of incoherence is always present. It has been shown by Tamor (1973) and Thomson *et al.* (1974) that the effects of the finite bandwidth $\Delta\omega_0$ of the incident field on the parametric instabilities can be taken care of by replacing the damping rate of the waves Γ_ϱ by $(\Gamma_\varrho+2\xi)\sim(\Gamma_\varrho+\Delta\omega_0)$ where ξ is the number of phase jumps per unit time. It is so because Γ_ϱ is a measure of the duration of time an electron is allowed to oscillate with the driving field before being knocked out of phase by a collision. The same effect results when the driving field suffers a phase shift and the two effects are additive. Thus replacing Γ_ϱ by $(\Gamma_\varrho+\Delta\omega_0)$ certainly raises the threshold for the instability and equation (6) is modified to

$$(K\lambda_{\mathrm{D}})\times3.86\times10^{11}\frac{L_{41}}{\gamma_{\mathrm{pc}}^2 T_4}\geq\Gamma_\varrho\Gamma_a\left(1+\frac{\Delta\omega_0}{\Gamma_\varrho}\right)$$

and the anomalous absorption rate decreases to

$$\gamma_{\mathrm{an}}=\frac{[(\Gamma_a\Gamma_\varrho)_{\max}]^{1/2}}{c}\,\frac{1}{(1+\Delta\omega_0/\Gamma_\varrho|_{\max})}$$

$$\simeq2\times10^{-5}\left(\frac{L_{41}K\lambda_{\mathrm{D}}}{T_4\gamma_{\mathrm{pc}}^2}\right)^{1/2}\frac{1}{(1+\Delta\omega_0/\Gamma_\varrho)|_{\max}}.$$

For the numerical example taken here, at $\Delta\omega_0/\Gamma_\varrho|_{\max}=10^2$, the anomalous absorption rate becomes comparable to the free–free absorption rate. Thus the parametric decay instability will operate from $\Delta\omega_0=0$ to $\Delta\omega_0=10^7$ since $\Gamma_\varrho|_{\max}\sim10^5$. If the bandwidth exceeds this value, the free–free process takes over. One must remember that this limit in $\Delta\omega_0$ depends on the characteristics like the luminosity, the distance of the emission-line regions and the frequency of the incident radiation. Thus the restriction on the bandwidth is not very stringent in view of the fact that the large luminosity radiation is believed to be generated by coherent emission processes. Another source of incoherence of the electromagnetic radiation is the lack of definite polarization. In an unpolarized beam, the tip of the electric vector undergoes random changes of direction. Thus an electron in such a field undergoes changes in its direction of motion at the same rate. This essentially increases the effective collision frequency of the electrons and thus raises the threshold for the decay instability. In the case of quasars, 1–10 per cent of the radiation is believed to be polarized. This means that 1–10 per cent of the total luminosity is actually available for the excitation of the decay instability. One notices that equation (6) for the threshold luminosity is easily satisfied even when L_{41} is taken to be 0.01 for 1 per cent polarized radiation.

4 Conclusion

The anomalous absorption rate of the radio waves near the electron plasma frequency is much larger than the free–free absorption rate. Electron temperature can increase by a factor of 5.5 for a moderate radio luminosity of 10^{41} erg s^{-1}. For a smaller value of the luminosity, the low-density regions situated closer to the central object get much more heated than the high-density regions. Decay instability may be the mechanism for the formation of hot lower density corona adjoining each photoionized dense region. This mechanism is also likely to be operating in the BL Lacertae objects where the absence of dense gas clouds is attributed to the strong radio frequency heating (Krolik *et al.* 1978). In addition the low-frequency turnover attributed to synchrotron self-absorption is a commonly observed feature of the most of the non-thermal radio sources believed to be emitting via synchrotron processes. In the case of quasars, the radio luminosity is found to be less than that expected from the extrapolation of the spectrum from high frequencies to low frequencies. Therefore absorption is certainly there and anomalous absorption might modify the spectrum in a significant way. But, as the emission-line regions have a small filling factor around the quasar, most of the radiation manages to leak out from in between the regions.

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