Mon. Not. R. astr. Soc. (1988) **231,** 353–357

Is 21-cm absorption associated with the emission-line regions of quasars?

V. Krishan *Indian Institute of Astrophysics, Bangalore 560034, India*

Accepted 1987 September 15. Received 1987 September 10; in original form 1987 April 7

Summary. The 21-cm absorption line observed in several QSO systems is believed to originate in neutral hydrogen clouds in the vicinity of the QSOs. The aim of this paper is to show that 21-cm absorption can also originate in a highly ionized emission-line region with electron plasma frequency close to 1420 MHz (21 cm), through the process of parametric decay instability. This absorption process has a line character in principle since it occurs only when a frequency-matching condition is satisfied. The width of the absorption feature results from the width of the electron density distribution function of the emission-line region. The absorption coefficient for the parametric decay process is much larger than that for the spin–flip transition. A part of the radio continuum is therefore depressed because this absorption process occurs over a range of frequencies.

1 Introduction

The standard interpretation of the 21-cm absorption observed in several QSO systems is that it originates in the neutral hydrogen clouds in the environs of the QSO (Weymann, Carswell & Smith 1981). In this paper, I show that the emission-line region is a very likely site for absorption of 21-cm radiation. An electromagnetic wave is subjected to collisional absorption in a plasma but this absorption is in the form of a continuum. 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 electron plasma oscillations which can become unstable and grow to large amplitudes. Eventually, these electron plasma waves undergo Landau damping, heating the plasma in the process (DuBois & Goldman 1965; Kaw & Dawson 1969). The absorption is essentially at the electron plasma frequency of the plasma. I propose that 21-cm (1420-MHz) radiation will be absorbed in a plasma of electron plasma frequency 1420 MHz and the emission-line region is an ideal site for such absorption to occur. In Section 2, I consider the parametric decay of a radio wave into an electron plasma wave and an ion-acoustic wave. In Section 3, I show how an observed 21-cm absorption profile can be generated through the spatial variation of electron density in the emission-line region.

2 Parametric decay instability

This mechanism has been considered earlier in a search for an additional heating mechanism of the emission-line region (Krishan 1987). The parametric decay of the radio waves can be described as:

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

where (ω_0, $\mathbf{K}_0$) is the frequency and wave vector of the incident radiation,

$$\omega_0^2=\omega_{pe}^2+K_0^2C^2; \qquad \omega_e^2=\omega_{pe}^2+3K^2V_e^2,$$

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

$$\omega_{pi}^2=\frac{4\pi ne^2}{m_i}, \qquad \lambda_D=V_e/\omega_{pe}.$$

Since $\omega_0\simeq\omega_{pe}$, $K_0\simeq 0$ and $|\mathbf{K}|=|\mathbf{K}_e|=|\mathbf{K}_i|$. 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)

$$(\omega^2+2i\omega\Gamma_a-K^2C_s^2)(\omega-\Delta+i\Gamma_p)+\frac{(\mathbf{K}\cdot\mathbf{V}_0)^2\omega_{pi}^2}{2\omega_{pe}}=0, \tag{2}$$

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_p is the damping rate of the electron plasma wave, Γ_a is the damping rate of the ion wave, and $C_s=(T_e/m_i)^{1/2}$. $V_0=(eE_0/m_e\omega_0)$ 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 maximum growth rate $\gamma_{an}=\mathrm{Re}\,\delta$ which is also the absorption rate of the incident wave [the details of the calculations can be found in Krishan (1987)]:

$$\gamma_{an}\simeq 2\times 10^{-5}\left(\frac{L_{41}K\lambda_D}{r_{pc}^2T_4}\right)^{1/2}\ \mathrm{cm}^{-1}, \tag{3}$$

where the luminosity of the incident radiation $L=L_{41}\times 10^{41}\ \mathrm{erg\,s^{-1}}$; the plasma temperature $T_e=T_i=T_4\times 10^4$ K and the distance between the source of incident radiation and the emission-line region is $r_{pc}\times 3\times 10^{18}$ cm. For comparison, the absorption rate for the spin–flip transition is given as

$$k(\omega)=2.58\times 10^{-15}\frac{f(\omega)N}{T_K}\ \mathrm{cm}^{-1}, \tag{4}$$

where T_K is the temperature which characterizes the population distribution between the two atomic states, $f(\omega)$ is the line-shape function normalized to unity, and N is the number of hydrogen atom cm^{-3}. One can check that the absorption rate for the parametric decay process is much larger than that for the spin–flip transition for standard values of the parameters.

3 21-cm absorption profile

Absorption of radio radiation by parametric decay into an electron plasma wave and an ion-acoustic wave certainly has a line character, since only that spectral portion which satisfies equation (1) gets absorbed. Thus the plasma, depending upon its electron density, picks up electromagnetic radiation of the right frequency. The width of the absorption feature corresponds to the width of the electron density variation in the plasma. I shall now derive the electron density profile which produces the observed absorption spectrum of the 21-cm radiation. One observes that the absorption rate (equation 3) depends on electron density only through the factor $K\lambda_0 \ll 1$ and therefore has a weak density dependence. This is due to the fact that resonance conditions (equation 1) have been used. We therefore conclude that the major density dependence of the optical depth is through the path length $S(n)$. Thus the optical depth τ is given by

$$\begin{aligned}\tau(\omega) &= \gamma_{\mathrm{an}}\, S(\omega)\\ &\equiv \gamma_{\mathrm{an}}\, S(n).\end{aligned} \tag{5}$$

The 21-cm optical depth can be written as

$$\tau = -\ln\left(1 - \frac{\Delta T_{\mathrm{a}}}{T_{\mathrm{a}}}\right) \tag{6}$$

where T_{a} is the flux incident on the absorber and ΔT_{a} is the observed peak brightness of the profile. For a numerical example, we take the data from Wolfe, Briggs & Jauncey (1981) who have reported measurements on 21-cm absorption in the QSO PKS 1157+014 at $z = 1.94$. They have fitted the line profile with a single Gaussian function characterized by a velocity dispersion $\sigma_V = 17.9 \pm 1.3\,\mathrm{km\,s^{-1}}$ which corresponds to FWHM $\Delta V_{\mathrm{c}} = 42 \pm 3\,\mathrm{km\,s^{-1}}$, the depth of the Gaussian function is given as $\Delta T_{\mathrm{a}} = 0.135 \pm 0.009\,\mathrm{K}$ and $T_{\mathrm{a}} = 2.8\,\mathrm{K}$. Thus ΔT_{a} can be written as

$$\Delta T_{\mathrm{a}} = 0.135 \exp\left[-\frac{(\Delta V)^2}{8\sigma_V^2}\right]. \tag{7}$$

Now the velocity distribution function can be converted into a frequency distribution function which then can be related to an electron density distribution as follows:

$$\frac{(\Delta V)^2}{\sigma_V^2} = \frac{(\Delta\omega)^2}{\sigma_\omega^2}, \qquad \sigma_\omega^2 = (4735)^2(18)^2 = 7.26\times10^9\,(\mathrm{s^{-1}})^2$$

$$\begin{aligned}(\Delta\omega)^2 = (\omega-\omega_0)^2 &= \frac{4\pi e^2}{m_{\mathrm{e}}}\left[\frac{1}{4}\frac{(\Delta n)^2}{n_0}\right]\\ &= 0.75\times10^9\, n_0\left(\frac{\Delta n}{n_0}\right)^2.\end{aligned} \tag{8}$$

Since the frequency ω of the electromagnetic radiation is close to the electron plasma frequency,

$$\omega_0 = \left(\frac{4\pi n_0 e^2}{m_{\mathrm{e}}}\right)^{1/2}$$

is the frequency corresponding to the maximum in absorption, and Δn is the departure from the central density n_0. We take $n_0 = 6.72\times10^8\,\mathrm{cm^{-3}}$ to correspond to $\omega_0 = 1420\,\mathrm{MHz}$. Substituting equations (7) and (8) into equation (6) one gets the frequency or the density dependence of the optical depth as

$$\tau = -\ln\left\{1 - 0.048 \exp\left[-\frac{0.75\times10^9}{8\sigma_\omega^2}\, n_0\left(\frac{\Delta n}{n_0}\right)^2\right]\right\} \tag{9}$$

or

$$\tau = -\ln\left\{1 - 0.048 \exp\left[-8.73\times10^6\left(\frac{\Delta n}{n_0}\right)^2\right]\right\}. \tag{10}$$

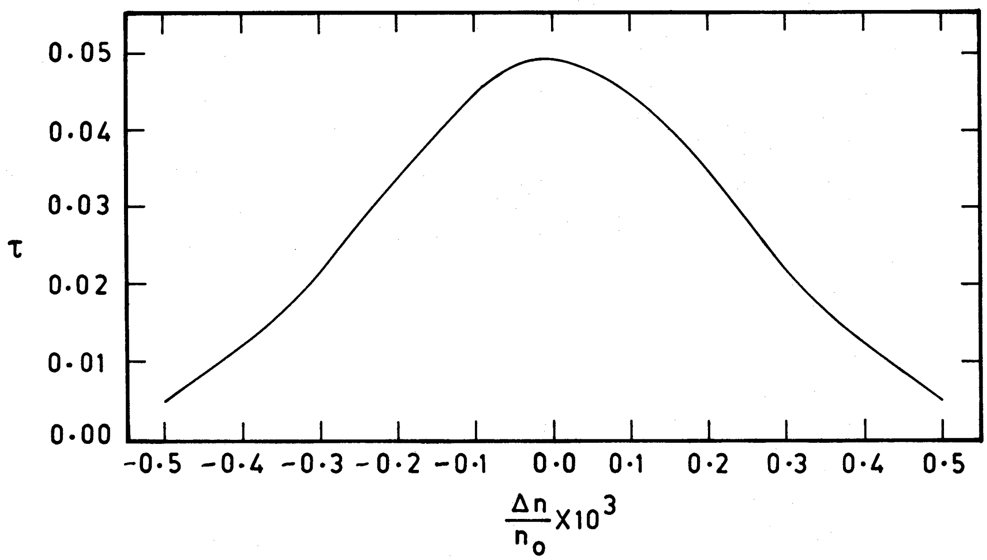

Figure 1. Spatial variation of electron density deduced from 21-cm absorption in the emission-line region.

Using equation (5) we derive the spatial variation of electron density in the emission-line region. This variation is shown in Fig. 1. Thus the electron density profile is such that the path length is largest at the central frequency (1420 MHz) and decreases for both higher and lower frequencies. The length scale of density variation for $\gamma_{\rm an} \sim 10^{-5}$ is found to be

$$\left(\frac{\Delta n}{n_0 \Delta S}\right)^{-1} \sim 10^7\,\mathrm{cm},$$

which is rather small. This is because the absorption process is a collective effect and thus extremely fast.

From equations (7) and (8), one finds that $\Delta T_{\rm a}$ falls to $(\Delta T_{\rm a}|_{\rm max}/10)$ for $\Delta n/n_0 \sim 5\times10^{-4}$. Thus it is possible to reproduce the observed absorption profile of 21-cm radiation from a plasma of electron density $(n \pm \Delta n)$ where $\Delta n = 3.6\times10^5\,\mathrm{cm}^{-3}$. This is a rather special demand on the electron density variation. One does not expect the electron density to have such a sharp profile in the environs of a quasar. The absorption would therefore occur over a range of frequencies depending upon the covering factor and the spread in the electron density. The 21-cm line is not preferentially affected because of the inherent large spread in the electron density. The parametric decay absorption thus results in the reduction of a part of the radio continuum depending on the covering factor.

4 Conclusions

(i) A strong electromagnetic wave of frequency close to the electron plasma frequency is susceptible to decay into an electron plasma wave and an ion-acoustic wave while passing through a plasma. For 21-cm radiation, a portion of the emission-line region provides such a plasma.

(ii) Since the parametric decay is a collective process, the absorption rate of the electromagnetic wave is extremely high. As a result the effective absorption occurs over much shorter path lengths in the line-of-sight. This has implications for the shape of the absorbing plasma.

(iii) The neutral hydrogen clouds are much further from the source of continuum 21-cm radiation than the emission-line region. Therefore 21-cm radiation will be first intercepted by the emission-line region and will undergo strong absorption through the parametric decay process.

The radio-emitting region, being of large size, may overlap a significant portion of the emission-line region. The radiation that leaks through is available to be absorbed in the H I region.

(iv) It has been inferred from emission-line studies that this region has a range of electron densities. In this case the absorption from each region will be superimposed and the profile may be broadened beyond recognition.

(v) We may conclude that, since the conditions for the parametric decay process to occur are satisfied, absorption of 21-cm radiation will take place in the emission-line region. If so, then absorption of 21-cm radiation cannot be attributed entirely to neutral hydrogen.

References

DuBois, D. & Goldman, M., 1965. *Phys. Rev. Lett.*, **14,** 544.
Kaw, P. K. & Dawson, J. M., 1969. *Phys. Fluids,* **12,** 2586.
Krishan, V., 1987. *Mon. Not. R. astr. Soc.*, **226,** 629.
Liu, C. S. & Kaw, P., 1976. *Adv. Plasma Phys.*, **6,** 83.
Weymann, R. J., Carswell, R. F. & Smith, M. G., 1981. *Ann. Rev. Astr. Astrophys.*, **19,** 41.
Wolfe, A. M., Briggs, F. H. & Jauncey, D. L., 1981. *Astrophys. J.*, **248,** 460.