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The Cerenkov iron Kα line in Active Galactic Nuclei – calculation in the optically thin case

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Abstract. In this paper we continue the research on the Cerenkov origin of the iron Kα line in AGNs. We claim again that the newly recognized line emission mechanism, Cerenkov line-like radiation, could be significantly responsible for the observed iron K-lines of AGNs. We give a new model calculation of the luminosity of the iron Kα line in the optically thin condition, which is an important extension of our previous calculation in the optically thick case. The new calculation is also comparable to the typical observed luminosity of iron Kα line, thus confirming the effectiveness of the new mechanism. Besides, we analyze a possible negative influence of the hydrogen-dominated plasma upon the efficiency of Cerenkov line-like radiation in detail, which was ignored in our previous paper (You et al. 2003). We conclude that such a negative effect of the plasma oscillation is unimportant and can be neglected.

Key words. line: formation – radiation mechanism: non-thermal – X-rays: galaxies – galaxies: Seyfert – black hole physics

1. Introduction

Observations show a feature peaked around ~6.4−6.5 keV in the spectra of active galactic nuclei (AGNs), that is commonly attributed to the Kα line of iron ions in low or intermediate ionization states. The iron Kα line as observed by ASCA displayed some interesting characteristics: the line is very broad with an asymmetric line profile, steep on the blue side and with a flattening red wing, extending to 4−5 keV (e.g., Tanaka et al. 1995; Nandra et al. 1997a,b; Fabian et al. 2002; Wang et al. 2001). However the updated observations from both XMM-Newton and Chandra show much narrower iron K-lines in many AGNs (e.g., Yaqoob et al. 2001; Terashima et al. 2002; Reeves 2002; Turner et al. 2002; O'Brien et al. 2001). Some authors claim that the AGNs with narrow iron K-lines are in the majority (e.g. Reeves 2002). The iron Kα line is regarded as one of the best probes to explore the physical mystery in regions near to the central supermassive black holes of AGNs. Lately much attention has therefore been given in the study of black hole physics and AGNs to the observation and interpretation of this line. In the prevailing "reflection disk-fluorescence line" models, the observed iron lines are commonly attributed to the reprocessing of the incident X-ray continuum by the irradiated disk. However, in our recent paper (You et al. 2003, hereafter Y03), we argued that a new line emission mechanism, Cerenkov line-like radiation, could well be responsible for the production of the iron lines in AGNs. In Y03, we gave an outline of the physics of the Cerenkov line-like radiation for people who are unfamiliar with this new emission mechanism. Some important formulae for this mechanism were given in the Appendix of Y03. The detailed theoretical derivations were given in another paper (You et al. 2000, hereafter Y00).

In Y03, we presented a model calculation of the Cerenkov iron Kα line in the optically thick case. The calculated Cerenkov line luminosity is comparable to the line luminosities observed in AGNs. Our initial success encouraged us to carry out further modelling. For example, in Y03 we ignored the optically thin case, which should be as important as the optically thick case because so far the environments of AGNs are not very clear yet. In the scenario shown in Fig. 4 of Y03 the size and the gas density of each dense cloudlet or filament in the spherical emission region cannot be determined in advance. We cannot exclude the possibility that there are optically thin cloudlets/filament. In other words, it is possible that the size L of the cloud could be less than the mean free path of the Cerenkov line photon, $L < l \sim 1/k$, where $k = k_{lu} + k_{\rm bf}$ is the total real absorption for the Cerenkov line (see Y03). We want to know whether the Cerenkov line-like radiation mechanism in the optically thin case is still sufficiently efficient to produce an iron Kα line that is strong enough to compare with observations. We also want to know whether the new scenario of AGNs described by the physical parameters in the optically thin condition is compatible with other observation facts.

Besides, we notice that, for an almost fully ionized hydrogen-dominated plasma, the well-known plasma oscillation makes a negative contribution to the refractive index of gas, or even causing the index n to become <1; thus the Cerenkov line-like radiation could be markedly weakened, or even disappear. Therefore, in this paper we have to evaluate the influence of the hydrogen plasma on the efficiency of the Cerenkov line-like radiation.

In Y03, we simply assumed the size of the emitting region to be $D \approx 3 \times 10^{15}$ cm for AGNs with a broad iron K-line. However, the narrow iron K-lines observed in recently years indicate a more distant line-emission region, far from the central black hole. In this paper we add the calculation for the narrow-iron-line AGNs, assuming a typical distance $D \approx 10^{17}$ cm (see Sect. 2.3).

This paper is organized as follows: in Sect. 2 we give a re-calculation of the Cerenkov iron Kα line in the optically thin condition, and compare it with observations. This is an important extension of our previous paper Y03. Calculations for both the broad and the narrow iron Kα lines are presented. Besides, we give a detailed analysis of the possible negative influence of the hydrogen plasma on the efficiency of the Cerenkov mechanism. We want to know whether the hydrogen plasma oscillation can weaken the Cerenkov line radiation. In Sect. 3 is we provide conclusions and discussions. We emphasize again the reliability and the acceptability of the new scenario of the environment around the central black hole, described by the parameters used in the new calculation.

2. Model calculation of the luminosity of the Cerenkov iron Kα line in the optically thin case

A detailed discussion of the physics of the Cerenkov line-like radiation and the main formulae describing the properties of the Cerenkov iron Kα line have been given in Y03. In this paper, we re-list the relevant formulae, necessary for the following model calculation, but omit the derivations and explanations of these formulae. We emphasize again that the CGSE system of units is used in the following formulae. This means, in particular, that the energy $\epsilon = h\nu$ of an X-ray photon will be in ergs rather than keV (1 keV = 1.602×10^{-9} erg).

2.1. Cerenkov spectral emissivity and absorption coefficient

The key point of the calculation of the spectrum of the Cerenkov radiation is the evaluation of the refractive index of a gaseous medium. This is easy to understand qualitatively from the necessary condition for producing the Cerenkov radiation, $v > c/n_\nu$. At a given frequency ν, the larger the index n_ν, the easier it is to satisfy the condition $v > c/n_\nu$, and the stronger the Cerenkov radiation at ν will be. Therefore, in order to get the theoretical spectrum of the Cerenkov radiation, it is necessary to calculate the refractive index n_ν and its dependence on ν, i.e., the dispersion curve $n_\nu \sim \nu$. For a gaseous medium, the calculation is easy to do. Omitting the detailed derivation (see Y00, or Y03), we simply present a good approximate analytical formula for the refractive index of gas in the narrow region close to the intrinsic energy of the iron line $\epsilon \approx \epsilon_{lu}$

$$n_\nu^2 - 1 = \frac{c^3 h^4}{16\pi^3} \epsilon_{lu}^{-4} A_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right) y^{-1} = C_0 y^{-1} \quad (\text{when } y \geq 10^{-5}) \qquad (1)$$

where

$$C_0 \equiv \frac{c^3 h^4}{16\pi^3} \epsilon_{lu}^{-4} A_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right) = 1.05 \times 10^{-76} \epsilon_{lu}^{-4} A_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right)$$

$\epsilon_{ul} \equiv h\nu_{ul} = \epsilon_u - \epsilon_l$ represents the energy of the line photon, i.e. the energy difference of the upper and lower levels of the iron ion. A_{ul} is the Einstein spontaneous emission coefficient for $u \to l$. $\Gamma_{ul} = \Gamma_u + \Gamma_l = \sum_{i<u} A_{ui} + \sum_{j<l} A_{lj}$ is the quantum damping constant for the atomic (ion) line with energy ϵ_{ul}, which is related with the Einstein spontaneous emission probabilities A_{ui} and A_{lj}. N_{Fe} is the number density of iron ions in gas. g_u (or g_l), and S_u (or S_l) are the degeneracy and the actual occupation number of electrons of the upper level u (or lower level l), respectively. $y \equiv \frac{\Delta\lambda}{\lambda_{ul}} = -\frac{\Delta\nu}{\nu_{ul}} = -\frac{\Delta\epsilon}{\epsilon_{ul}} = \frac{\epsilon_{lu}-\epsilon}{\epsilon_{lu}}$ represents the fractional displacement of the frequency or photon-energy. $y \ll 1$ owing to the fact that Cerenkov line-like radiation is concentrated in a narrow band $\epsilon \approx \epsilon_{ul}$.

In the formula shown above we neglected the contributions of all other species of atoms and ions in gas, especially hydrogen. The validity of neglecting these is discussed in Sect. 2.4 below.

The Cerenkov spectral emissivity can be obtained from the dispersion curve $n_\nu \sim \nu$ given by Eq. (1). Omitting the detailed derivation, we obtain

$$J_y^{\mathrm{c}} \mathrm{d}y = C_1 N_{\mathrm{e}} \left(y^{-1} - y_{\mathrm{lim}}^{-1} \right) \mathrm{d}y \ (\text{valid for } y \geq 10^{-5}) \qquad (2)$$

where

$$C_1 \equiv \frac{e^2 c^2 h^2}{16\pi^2} \epsilon_{lu}^{-2} A_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right) = 5.77 \times 10^{-53} \epsilon_{lu}^{-2} A_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right)$$

N_{e} is the density of fast electrons. y_{lim} is the fractional Cerenkov line-width which is related to the real Cerenkov line-width $\Delta\epsilon_{\mathrm{lim}}$ by the relation $y_{\mathrm{lim}} \equiv -\frac{\Delta\epsilon_{\mathrm{lim}}}{\epsilon_{ul}}$, and

$$y_{\mathrm{lim}} = C_0 \gamma_{\mathrm{c}}^2 \qquad (3)$$

where γ_{c} is the typical or average energy of the fast electrons moving in the gas. C_0 is given in Eq. (1) (see Y00 or Y03).

The line absorption coefficient in the vicinity of the atomic line is (Y00 or Y03)

$$k_{lu} = \frac{c^2 h^4}{32\pi^3} \epsilon_{lu}^{-4} A_{ul} \Gamma_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right) y^{-2} = C_2 y^{-2} \qquad (4)$$

where

$$C_2 \equiv \frac{c^2 h^4}{32\pi^3} \epsilon_{lu}^{-4} A_{ul} \Gamma_{ul} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right) = 1.75 \times 10^{-87} \epsilon_{lu}^{-4} A_{ul} \Gamma_{lu} g_u N_{\mathrm{Fe}} \left(\frac{S_l}{g_l} - \frac{S_u}{g_u} \right).$$

From Eq. (4) we see that the line absorption becomes very large when $y \to 0$.

Another kind of absorption for the Cerenkov line photons is the photoelectric absorption $k_{\rm bf}$ (the free-free absorption $k_{\rm ff}$ in the X-ray band is negligibly small). For the iron K-lines that we are concerned with the dominant photoelectric absorbers are the L-shell electrons of the iron ions. Therefore (Y00, or Y03)

$$k_{\rm bf} \approx k_{\rm bf}({\rm Fe}, L) = 8.4 \times 10^{-46} N_{\rm Fe} S_2 \epsilon_{lu}^{-3}. \tag{5}$$

From Eq. (5) we see that the photoelectric absorption $k_{\rm bf}$ is almost constant in the narrow frequency band of the Cerenkov line $\epsilon \approx \epsilon_{lu}$.

The total absorption coefficient for the Cerenkov line thus becomes

$$k = k_{lu} + k_{\rm bf} \approx C_2 y^{-2} + k_{\rm bf}({\rm Fe}, L). \tag{6}$$

2.2. The elementary luminosity of the Cerenkov iron Kα line from a single cloud; calculation in the optically thin case

In the following calculations, we adopt the same model as shown in Fig. 4 in our previous paper Y03, i.e., a lot of dense cloudlets with typical radius r distributed in a quasi-spherical emission region around the central black hole of an AGN. Denoting the size of emission region as D and the radius of each dense cloud as r, respectively, for an optically thin cloud r, according to Eq. (2), the emergent spectral luminosity is

$$l_y^{\rm c} {\rm d}y = \left(\frac{4\pi}{3} r^3\right)(4\pi j_y^{\rm c} {\rm d}y) = \frac{16\pi^2}{3} r^3 C_1 N_{\rm e} \left(y^{-1} - y_{\rm lim}^{-1}\right) {\rm d}y. \tag{7}$$

However, we notice that Eq. (7) is no longer valid in the tightest vicinity of the intrinsic energy $\epsilon \to \epsilon_{lu}$. According to Eq. (4), the absorption coefficient $k \to \infty$ when $y \to 0$, which means that the optically thin condition would be destroyed for $\epsilon \to \epsilon_{lu}$ i.e., $y \to 0$. Defining $\tau \equiv kr = \left(C_2 y^{-2} + k_{\rm bf}\right) r$ as the optical radius to describe the opacity of the cloudlet to the Cerenkov iron line, in any case $\tau > 1$ as long as $y \to 0$, irrespective of what values of $N_{\rm Fe}$ and r are taken, i.e., the cloud approaches to optically thick when $y \to 0$. For $\tau \equiv kr = \left(C_2 y^{-2} + k_{\rm bf}\right) r \approx C_2 y^{-2} r = 1$, we get a critical minimum value $y = y_{\rm min}$

$$y_{\rm min} = \sqrt{C_2 r}. \tag{8}$$

In the narrow frequency region $0 < y < y_{\rm min}$, $\tau > 1$, the cloud becomes optically thick, most Cerenkov line photons in this band would be absorbed; only in the dominant region of the Cerenkov line, $y_{\rm min} < y < y_{\rm lim}$, $\tau < 1$, does the optically thin condition hold. Neglecting the weak Cerenkov radiation in the region $0 < y < y_{\rm min}$, and using Eq. (7), the total luminosity of the Cerenkov iron Kα line of a single cloud is approximately

$$\begin{aligned} l_{{\rm K}\alpha}^{\rm c} &\approx \int_{y_{\rm min}}^{y_{\rm lim}} l_y^{\rm c} {\rm d}y = \frac{16\pi^2}{3} r^3 C_1 N_{\rm e} \int_{y_{\rm min}}^{y_{\rm lim}} \left(y^{-1} - y_{\rm lim}^{-1}\right) {\rm d}y \\ &= \frac{16\pi^2}{3} r^3 C_1 N_{\rm e} \left(\ln \frac{y_{\rm lim}}{y_{\rm min}} - \frac{y_{\rm lim} - y_{\rm min}}{y_{\rm lim}}\right) \\ &\approx \frac{16\pi^2}{3} r^3 C_1 N_{\rm e}. \end{aligned} \tag{9}$$

The last approximation step in Eq. (9) corresponds to the natural assumption of $y_{\rm lim} \gg y_{\rm min}$. Condition $y_{\rm lim} \gg y_{\rm min}$ gives an upper limit for the radius of an optically thin cloud

$$r \le \frac{y_{\rm lim}^2}{C_2}. \tag{10}$$

Therefore, for a given iron density $N_{\rm Fe}$, the cloudlet will be optically thin in the main radiation band $y_{\rm min} < y < y_{\rm lim}$ when its radius r is less than the upper limit given in Eq. (10), which ensures Eq. (9) to be true.

2.3. Total luminosity of the Cerenkov iron Kα line

Following Y03, we denote the total number of dense cloudlets in the whole spherical emission region around the central black hole as $\tilde{N}$, the radius of each cloudlet as r, thus the covering factor is $f_{\rm c} = \tilde{N} \frac{r^2}{4D^2}$. Therefore the total luminosity of the Cerenkov iron Kα line emergent from the whole emission region is

$$L_{{\rm K}\alpha}^{\rm c} = \frac{16\pi^2}{3} r^3 C_1 N_{\rm e} \tilde{N} = \frac{64\pi^2}{3} C_1 N_{\rm e} f_{\rm c} D^2 r. \tag{11}$$

As in Y03, we take the typical values of $f_{\rm c} = 0.1$, $D = 3 \times 10^{15}$ for the AGNs with a broad Kα line, for which the typical observed timescale of variability is $\sim 1d$, corresponding to $D \sim 3 \times 10^{15}$ cm. The value of r is constrained by Eq. (10), which corresponds to the critical case $\tau \le 1$ in the region $y_{\rm min} < y < y_{\rm lim}$. Therefore from Eq. (11) we obtain the upper limit of the total Cerenkov iron line in the limiting optically thin case

$$\begin{aligned} L_{{\rm K}\alpha} &\le \frac{64\pi^2}{3} C_1 N_{\rm e} f_{\rm c} D^2 \frac{y_{\rm lim}^2}{C_2} \\ &= 1.7 \times 10^{-21} N_{\rm e} N_{\rm Fe}^2 \gamma_{\rm c}^4 \left(1 - \frac{S_2}{g_2}\right)^2. \end{aligned} \tag{12}$$

Comparing Eq. (12) with the typical observed value $L_{{\rm K}\alpha}^{\rm obs} \approx 10^{40-41}$ erg/s, and letting $L_{{\rm K}\alpha}^{\rm c} \approx L_{{\rm K}\alpha}^{\rm obs}$, we get the constraint condition for the parameters in the calculation

$$N_{\rm e} N_{\rm Fe}^2 \gamma_{\rm c}^4 \gtrsim 10^{62}. \tag{13}$$

Equation (13) gives the combined condition for the parameters $N_{\rm e}$, $N_{\rm Fe}$ and $\gamma_{\rm c}$ for obtaining a value of luminosity of the Cerenkov iron Kα line in the critical optically thin case that matches the typical observed value. Therefore the Cerenkov line-like radiation is also efficient even in the optically thin condition, as long as the density $N_{\rm e}$ and the energy $\gamma_{\rm c}$ of fast electrons and the iron density $N_{\rm Fe}$ are high enough to satisfy the inequality Eq. (13). Table 1 shows some possible sets of parameters for the condition Eq. (13), where we arbitrarily fix $N_{\rm e} = 10^{12}$ cm^{-3} because so far the environments in AGNs are not well understood.

Similar calculations for the narrow iron Kα line AGNs are also completed with a different set of typical values $f_{\rm c} = 0.1$, $D = 10^{17}$ cm. The change of D from $\sim 3 \times 10^{15}$ to $\sim 10^{17}$ cm is owing to the fact that the observed line width of the narrow iron line in AGNs indicates that the narrow iron lines arise from a more distant region with $D \sim 10^{17}$ cm or $10^4 r_{\rm g}$ for a typical supermassive central black hole with mass $M \sim 10^8 M_\odot$.

Table 1. Tentative parameter sets in the model calculations of the luminosity of the Cerenkov iron Kα line (for AGNs with broad iron lines).

$N_{\rm Fe}$	$\gamma_{\rm c}$	$N_{\rm e}$
10^{13}	10^6	10^{12}
10^{14}	3×10^5	10^{12}
10^{15}	10^5	10^{12}
10^{16}	3×10^4	10^{12}
10^{17}	10^4	10^{12}

Table 2. Tentative parameter sets in the model calculations of the luminosity of the Cerenkov iron Kα line (for AGNs with narrow iron lines).

$N_{\rm Fe}$	$\gamma_{\rm c}$	$N_{\rm e}$
10^{12}	10^6	10^{11}
10^{13}	3×10^5	10^{11}
10^{14}	10^5	10^{11}
10^{15}	3×10^4	10^{11}
10^{16}	10^4	10^{11}

So the maximum value of Cerenkov iron line luminosity in the optically thin case becomes

$$L_{{\rm K}\alpha} \le \frac{64\pi^2}{3}C_1N_{\rm e}f_{\rm c}D^2\frac{y^2_{\rm lim}}{C_2} = 1.9\times10^{-18}N_{\rm e}N^2_{\rm Fe}\gamma^4_{\rm c}\left(1-\frac{S_2}{g_2}\right)^2. \quad (14)$$

Differing from Eq. (13), now the constraint condition of the parameters becomes

$$N_{\rm e}N^2_{\rm Fe}\gamma^4_{\rm c} \gtrsim 10^{59}. \quad (15)$$

Table 2 shows some possible sets of parameters for condition Eq. (15).

2.4. Evaluation of the effect of hydrogen plasma on the radiation of the Cerenkov iron Kα line

In the above discussions we have neglected the influence of all other species of atoms and ions upon the refractive index of gas near the intrinsic frequency of the iron Kα line. In real astrophysical plasmas, various species of atoms coexist. The dominant component is hydrogen, which is almost fully ionized. In principle, the contribution of all the species of atoms (ions) to the refractive index of gas in the vicinity of the intrinsic frequency of the iron Kα line must be taken into account, particularly the hydrogen. Retaining the dominant terms in the formula for the refractive index of the gas, we get

$$n^2 = 1+\Delta_{\rm Fe}+\Delta_{\rm H}+\Delta_{\rm He}+\Delta_{\rm Ca}+\Delta_{\rm O}+...\approx 1+\Delta_{\rm Fe}+\Delta_{\rm H}$$

where $\Delta_{\rm Fe}$ is the contribution from iron ions, given by Eq. (1); $\Delta_{\rm H}\approx-\frac{\nu_p^2}{\nu^2_{{\rm FeK}\alpha}}$ is the contribution from the hydrogen plasma, $\nu_p=\sqrt{\frac{e^2}{\pi m}N_{\rm H^+}}$ is the H-plasma oscillation frequency, and $N_{\rm H^+}\sim N_{\rm e}$ is the proton (electron) density in the gas; for an almost fully ionized plasma, $N_{\rm H^+}\sim N_{\rm H}\sim N_{\rm gas}$. The contribution of the hydrogen plasma to the refractive index is negative, thus it partly offsets the positive term $\Delta_{\rm Fe}$. Therefore the possibility of producing the Cerenkov iron Kα line is determined by the competition between $\Delta_{\rm Fe}$ and $\Delta_{\rm H}$. However, we argue that, in comparison with $\Delta_{\rm Fe}$, negative $\Delta_{\rm H}$ could be negligibly small, particularly for astrophysical plasmas with abnormally high abundance of iron $\xi_{\rm Fe}$.

Table 3. The upper limit of hydrogen density $N^{\rm up}_{\rm H}$ for a given energy $\gamma_{\rm c}$. The negative effect on the Cerenkov line emission can be totally neglected if $N_{\rm H}<N^{\rm up}_{\rm H}$.

$\gamma_{\rm c}$	$N^{\rm up}_{\rm H}$ (cm^{-3})
3×10^3	3.3×10^{21}
10^4	3.0×10^{20}
3×10^4	3.3×10^{19}
10^5	3.0×10^{18}
3×10^5	3.3×10^{17}

The negative term contributed by the H-plasma is given by

$$\Delta_{\rm H} = -\frac{\nu_p^2}{\nu^2_{{\rm FeK}\alpha}} = -\frac{\frac{e^2}{\pi m}N_{\rm H^+}}{\nu^2_{{\rm FeK}\alpha}} = -3.36\times10^{-29}N_{\rm H^+}.$$

Therefore the condition for Cerenkov radiation becomes

$$n^2 = 1+\Delta_{\rm Fe}+\Delta_{\rm H} = 1+\Delta_{\rm Fe}-3.36\times10^{-29}N_{\rm H^+}\ge\beta^{-2}\approx1+\gamma_{\rm c}^{-2} \quad (16)$$

or

$$\Delta_{\rm Fe}\ge3.36\times10^{-29}N_{\rm H^+}+\gamma_{\rm c}^{-2}. \quad (17)$$

From Eq. (16) or (17) we see that the influence of H plasma upon the Cerenkov iron line emission can be totally neglected if $3.36\times10^{-29}N_{\rm H^+}\ll\gamma_{\rm c}^{-2}$. Obviously, such an inequality is too severe to get a reasonable value of the hydrogen density $N_{\rm H}\sim N_{\rm H^+}$. The constraint for $N_{\rm H}$ can be greatly loosened if we ignore the negligibly weak Cerenkov radiation in the tail part $y\sim y_{\rm lim}$. Anyway, this inequality is still very useful as it provides a permitted upper limit of the hydrogen density in the gas

$$N^{\rm up}_{\rm H}\le3.0\times10^{28}\gamma_{\rm c}^{-2}. \quad (18)$$

For a given energy $\gamma_{\rm c}$ of fast electrons, Eq. (18) shows that the negative effect of hydrogen plasma on the efficiency of Cerenkov iron line emission is negligibly weak if the gas density $N\sim N_{\rm H}$ is lower than $N^{\rm up}_{\rm H}$. Table 3 lists several sets of $(N^{\rm up}_{\rm H},\gamma_{\rm c})$ in a wide range of $\gamma_{\rm c}$, which indicate that the negative effect of the H plasma is actually unimportant even when the gas density $N_{\rm gas}\sim N_{\rm H^+}<N^{\rm up}_{\rm H}$ is as high as shown in Table 3.

Comparing Table 1 with Table 3, we see that, for any given value of $\gamma_{\rm c}$, in order to eliminate the negative effect of hydrogen plasma on the broad Cerenkov iron line emission, an anomalously high iron abundance $\xi_{\rm Fe}\equiv\frac{N_{\rm Fe}}{N_{\rm H}}\approx3\times10^{-4}>\xi_\odot$ is needed. On the other hand, from Tables 2 and 3 we see that, for the narrow iron line AGNs, a normal abundance $\xi_{\rm Fe}\approx3\times10^{-5}\approx\xi_\odot$

is good enough to avoid trouble from the hydrogen plasma-oscillation.

3. Conclusions and discussions

The calculation completed in this paper shows that, even when the gas clouds in the emission region are optically thin, the Cerenkov line-like radiation mechanism is still able to produce an iron emission line, strong enough to be comparable with the observations of AGNs, as long as the energy and density of fast electrons as well as the density of iron ions are moderately high to ensure the successful operation of the new mechanism. Besides, we notice that an anomalous iron abundance favors the successful operation of the Cerenkov line mechanism, particularly for the broad iron line AGNs, as mentioned in Sect. 2. The adopted parameters, $N_{\rm e}$, $\gamma_{\rm c}$, and $N_{\rm Fe}$ in our model calculations appear to be reasonable and acceptable as argued in Y03, although the new scenario of the environment near to the central black hole described by these parameters seems to be quite different from the prevailing paradigm of AGNs. For brevity, in this paper we do not repeat our arguments in Y03 but only emphasize the possibility of the existence of abnormally high iron-abundance in AGNs with broad iron lines. As mentioned in Sect. 2.4, if we set $N_{\rm e} = 10^{12}$ cm^{-3}, and comparing Table 1 with Table 3, for any given electron energy $\gamma_{\rm c}$, we find the required iron-abundance to be as high as $\xi_{\rm Fe} \approx 3 \times 10^{-4}$, i.e. ~(6−7) times the solar value. This is likely true in regions near to the central black hole of AGN where the broad iron line originates. O'Brien et al. (2001) claimed that an abnormal iron abundance $\xi_{\rm Fe} \approx 5\xi_{\odot}$ is needed in the outer part of the disk at $r \sim 50{-}1000 r_{\rm g}$ to produce the observed excessive narrow iron line in Mrk 359. If their assumption is reasonable, then a slightly higher abundance $\xi_{\rm Fe} \approx 3 \times 10^{-4} \approx (6{-}7)\xi_{\odot}$ in the inner region of AGNs, much closer to the central supermassive black hole, seems acceptable because some violent and energetic processes, e.g., mergers, type I SNe, etc., should frequently occur in this region, boosting the quick nuclear reactions and markedly increasing the iron abundance.

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