A&A 419, L9–L12 (2004)
DOI: 10.1051/0004-6361:20040132

Astronomy & Astrophysics

A possible feature of thermal matter in relativistic jets of radio-loud quasars

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Received 23 October 2003 / Accepted 4 April 2004

Abstract. It has been suggested that relativistic jets in quasars may contain a considerable amount of thermal matter. In this paper, we explore the possibility that the Kα line from the thermal matter may appear at tens of keV due to a high Doppler blue-shift. In the jet comoving frame, the energy density of photons originally emitted by the accretion disk and reflected off the broad line region clouds dominates over that of photons of other origin. We discuss the photoionization states of the thermal matter and find that the irons elements are neutral. The high metallicity in quasars enhances the possibility to detect the thermal matter in the relativistic jet in some radio-loud quasars. A highly Doppler blue-shifted Kα line may be detected. We make a prediction for 3C 273, in which the Kα line luminosity might be of the order 3.0×10^{44} erg s^{-1} with an equivalent width of 2.4 keV. Such a line could be detected in a future mission.

Key words. galaxy: radio galaxies: active – quasars – individual: 3C 273

1. Introduction

It is well known that the observed powerful relativistic jets are an important ingredient in radio-loud quasars. The non-thermal electrons are responsible for the multiwaveband radiation although the specific acceleration mechanism remains a matter of debate. Little attention has been paid to questions related to the thermal matter in the relativistic jets.

As an example of a galactic jet source, SS433 has been extensively studied both observationally and theoretically (Kotani et al. 1997; Brinkmann & Kawai 2000). *Chandra* discovered several lines from highly ionized atoms, such as Fe XXV, Fe XXIV, Co XIV, S XVI, Lyα and Lyβ, Ne X and Mg XI etc. (Marshall et al. 2002). The chemical composition in these jets definitely includes heavy elements rather than pure pair plasma. This could be explained by a model in which the emission lines are originally from the hot plasma expanding in the jet (Brinkmann & Kawai 2000; Memola et al. 2002). In radio-loud quasars, the case is highly uncertain. A heavy jet mainly composed of proton-electron plasma has been suggested by Celotti & Fabian (1993) based on the kinetic luminosities of jets found in a large VLBI sample. The absences of soft X-ray bumps in radio-loud quasars lead to the exclusions of a pure pair and pure proton-electron plasma, most likely, the relativistic jet is pair-dominated numberwise but still dynamically dominated by protons (Sikora & Madejski 2000). The measurement of polarization in a few objects seem to favor the pair plasma (Wardle et al. 1999; Hirotani et al. 1999), but the linear polarization strongly supports a normal plasma as the main composition (Fraix-Burnet 2002). Ruszkowski & Begelman (2002) find that the electron-proton and electron-positron jets can lead to the same circular and linear polarization in 3C 279.

There is growing interest in the presence of thermal matter in relativistic jets (Celotti et al. 1998). The thermal matter, as argued by Celotti et al. (1998), may be due to: 1) not 100% matter can be accelerated to relativistic energy; 2) non-thermal matter cools down and is thermalized before being reaccelerated; 3) some thermal matter might also be trapped at the base of the jet as they form and some are loaded by the surrounding external medium (but see Lyutikov & Blandford 2002 for a different view). Kuncic et al. (1997) used CLOUDY to make detailed calculations of emission lines from the thermal matter immersed in the non-thermal radiation field in the jet. The basic features are the presence of emission lines in the extreme ultraviolet band. However, the situation in radio-loud quasars may not be so simple. There are three types of possible sources for the *ionizing* photons in the relativistic jet: 1) synchrotron photons (Blandford & Königl 1979); 2) accretion disk photons (Melia & Königl 1989; Dermer & Schlickeiser 1993); 3) diffuse photons in the broad line region (Sikora et al. 1994).

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At present the observations do not allow to decide which might dominate in blazars. In the jets comoving frame the thermal matter sees photons originating from the disk and reflected by the clouds in the broad line region. These photons may dominate over the local synchrotron photons (Sikora et al. 1994). Moreover, it is of great interest to note that a high metallicity is common in quasars (Hamann & Ferland 1999).

In this paper, we show that the thermal matter in the jet is neutral and the observational features of the thermal matter will mainly be the presence of a highly Doppler shifted Kα line, which could be detected in some radio-loud quasars by future instruments.

2. Emission from thermal matter in jets

2.1. Ionization of thermal matter and Fe Kα line

Detailed constraints on temperature, density and size of the thermal matter in relativistic jets have been discussed by Celotti et al. (1998), who suggest that the thermal matter may exist as cold clouds. The microscopic properties of the surviving clouds in the relativistic jet depend on many processes. The density and size of the clouds are largely uncertain. In this paper, we take typical values for the density, temperature and the size as given by Celotti et al. (1998), e.g. $n_t = 10^{14}\ n_{t,14}\ \mathrm{cm}^{-3}$, $T = 10^5 T_5$ K and $R_{\rm th} = 10^9 R_{\rm th,9}$ cm. For illustration, we consider the clouds in the jet at a distance R from the central black hole, with $R = 10\ R_g = 1.5\times10^{15}$ cm, where $R_g = 1.5\times10^{14}$ (cm) m_9 and $m_9 = M_{\rm BH}/10^9\ M_\odot$. We approximate the Doppler factor $\mathcal{D}$ with the Lorentz factor Γ and take $\Gamma_{10} = \Gamma/10 \approx 1$.

The peak frequency of the thermal emission from such clouds in the jet will be $\Gamma kT \approx 0.1$ (keV)$\Gamma_{10}T_5$ in the observer's frame, where k is Boltzmann constant. If such a soft X-ray emission is absent in the observed continuum, the number of the cold clouds N_0 should be constrained by

$$N_0 \le 5.62\times10^8 L_{\rm SX,46}\Gamma_{10}^{-4}T_5^{-4}R_{\rm th,9}^{-2}, \tag{1}$$

where the soft X-ray luminosity $L_{\rm SX} = 10^{46}\ L_{\rm SX,46}$ erg s^{-1}. Assuming the jet geometry to be a cone with opening angle $\theta_j \sim 1/\Gamma$, the cross section radius of the jet is $a = \theta_j R$. Since the sound velocity inside the cold clouds is much less than that in the intercloud medium, the expansion of the clouds can be neglected. The filling factor of the thermal clouds in the jet volume is $f \approx \sum_i^{N_0}(4\pi/3)R_{\rm th}^3/\left(\pi R^3/3\Gamma^2\right) \approx 6.66\times10^{-8}\ \Gamma_{10}^2\ R_{\rm th,9}^3\ R_{15}^{-3}$, where $R_{15} = R/10^{15}$ cm and the opening angle is taken as $\theta \approx 1/\Gamma$, indicating that the jet is very clumped with thermal clouds as suggested by Celotti et al. (1998). These general constraints on the thermal matter are in agreement with those of Sikora et al. (1997).

According to the disk-corona model by Haardt & Maraschi (1993), most of the gravitational energy will be released in the hot corona as X-ray emission, and UV emission as reprocessed X-rays. We take a similar scenario for the accretion disks in flat spectrum radio quasars. As an example, we take the accretion rate $\dot{m} = L_{\rm bol}/L_{\rm Edd} = 0.2$, where the Eddington luminosity is $L_{\rm Edd} = 1.26\times10^{47}\ m_9$ (erg s^{-1}). The bolometric luminosity is then $L_{\rm bol} = 2.52\times10^{46}$ (erg s^{-1}). For simplicity we assume that half of the bolometric luminosity is released in X-rays, $L_{\rm X} = 1.26\times10^{46}\ m_9$ (erg s^{-1}), and the other half in optical/UV, $L_{\rm UV} = 1.26\times10^{46}\ m_9$ (ergs s^{-1}). Some of the disk emission will be reflected by the clouds in the broad line region.

Sikora et al. (1994) point out that the photons in the relativistic jet received from diffuse scattering of accretion disk photons in the BLR may dominate over the local synchrotron photons and the photons received directly from the disk. The nature of the BLR clouds remains open (Alexander & Netzer 1994; Baldwin et al. 2003), the covering factor $\xi \approx 0.1$ is indicated by the energy budget of emission lines from BLR clouds (Netzer 1990). The typical density and temperature are $n_e = 10^{11\sim12}$ cm^{-3} and $T = 10^{4\sim5}$ K in the clouds of BLR, and the ionized fraction of dimension is typically $\ell = 10^{12}$ cm. The Thomson scattering optical depth is $\tau_{\rm es} \equiv n_e\sigma_{\rm T}\ell \sim 0.1$, where $\sigma_{\rm T}$ is the Thomson cross section. Collin-Souffrin et al. (1996) calculate emergent spectra from an optically thin cloud (with solar abundances) radiatively heated in detail. They found that about 1% of the incident radiation will be reflected for a cloud with column density $\Sigma = 10^{22}$ g cm^{-2} (Thomson depth $\tau_{\rm es} \approx 0.006$) and the reflected amount is insensitive to the cloud's temperature. In the optically thin regime, the reflected flux will be approximately proportional to the optical depth. Therefore, the reflected fraction of the incident radiation from disk is $\mathcal{R} > 0.1$ for the BLR clouds with $\tau_{\rm es} \approx 0.1$. The energy density of the diffuse X-rays is $U_{\rm X} = L_{\rm X}^{\rm ref}/4\pi R_{\rm BLR}^2 c$, where $L_{\rm X}^{\rm ref} = \xi\mathcal{R}L_{\rm X}$, $R_{\rm BLR}$ is the scale of the BLR and c the light speed. In the jet frame, the energy density of the received X-rays by the thermal matter is then

$$U'_{\rm X} = \Gamma^2 U_{\rm X} = 0.9\ (\mathrm{erg\ cm^{-3}})\Gamma_{10}^2 L_{\rm X,44}^{\rm ref}R_{\rm 0.1pc}^{-2}, \tag{2}$$

where we take the reflected fraction of hard X-rays $\xi\mathcal{R} = 0.01$ conservatively, the BLR size $R_{\rm 0.1pc} = R_{\rm BLR}/0.1$pc and $L_{\rm X,44}^{\rm ref} = L_{\rm X}^{\rm ref}/10^{44}$ erg s^{-1}. The ionization parameter defined by

$$\Xi = \frac{U'_{\rm X}}{n_t kT} \approx 6.0\times10^{-4}\ \Gamma_{10}^2 L_{\rm X,44}^{\rm ref}R_{\rm 0.1pc}^{-2}n_{\rm t,14}^{-1}T_5^{-1}, \tag{3}$$

indicating that most of the atoms are neutral (Krolik & Kallman 1984) and the iron Kα line is at 6.4 keV. It is thus expected that the thermal clouds will maintain their temperatures.

2.2. Iron abundance and line luminosity

As shown by Monte Carlo simulation of Reynolds (1996), the iron Kα line is the most prominent among the emergent lines in the reprocessed spectrum. We neglect the lines of other elements since they are much fainter than the iron Kα line. We take the relative abundance of iron as $\mathcal{A} = Z_{\rm QSO}/Z_\odot$, where $Z_{\rm QSO}$ is the iron abundance of QSO and $Z_\odot = 3\times10^{-5}$. Krolik & Kallman (1987) (see also Liedahl 1999 for details) show that the Fe K-edge opacity is

$$\kappa_{\rm K_0} = 0.67\kappa_{\rm es}f(\Xi)\mathcal{A}\left(\frac{E}{E_{\rm K_0}}\right)^{-3} \tag{4}$$

where $\kappa_{es} = 0.34$ is the Thomson scattering opacity, and $f(\Xi)$ is a slow function of Ξ. The optical depth of one cold cloud is

$$\tau_K = 0.45 f(\Xi)\mathcal{A}_{10} n_{t,14} R_{t,9}, \quad (5)$$

where $\mathcal{A}_{10} = \mathcal{A}/10$. For simplicity we assume that the reflected spectrum as the photoionization source is in a simple form as $L'_E = L'_0 (E/E_0)^{-\gamma}$ within $E_0 \leq E \leq E_1$, where $\gamma \approx 0.7$ is the index of the reflected spectrum by the clouds in the BLR. In the jet's comoving frame, $\int L'_E \mathrm{d}E = \Gamma^2 L_X^{\rm ref}$, yielding $L'_0 = (1-\gamma)C_0 E_0^{-1}\Gamma^2 L_X^{\rm ref}(E_1/E_0)^{-\gamma}$, and $C_0 = \left[(E_1/E_0)^{1-\gamma} - 1\right]^{-1}$. The reflected spectrum is assumed to be the same as the incident radiation field. This may be not exact, but the accuracy is enough for the present goal since the Kα line flux mainly depends on the total energy of hard X-rays.

With the optical depth given by Eq. (5), the luminosity of the Kα line from N_0 clouds in the jets comoving frame will be given by

$$L'_{K\alpha} \approx \langle Y\rangle \tau_K L'_0 \frac{E_{K\alpha}}{\gamma+3}\left(\frac{N_0\delta\omega}{4\pi}\right) \quad (6)$$

where $\langle Y\rangle$ is the fluorescent yield for the production of Kα, $\delta\omega$ is the solid angle of one cloud subtended at the X-ray continuum source. In the observer's frame, the received luminosity is $L_{K\alpha}^{\rm obs} = \Gamma^4 L'_{K\alpha}$, i.e.

$$L_{K\alpha}^{\rm obs} = 3.0\times10^{44}\ ({\rm erg/s})\Gamma_{10}^6 \mathcal{A}_{10} n_{t,14} R_{th,9}^3 R_{15}^{-2} L_{X,44}^{\rm ref} \quad (7)$$

with $\langle Y\rangle \approx 0.6$, $f(\Xi) = 1.7$, $E_0 \approx E_{K\alpha}$, $E_1/E_0 = 100/6.4$ and $N_0 = 5.62\times10^8$. The observed energy of the Kα line will be $E_{K\alpha}^{\rm obs} \approx 64\ ({\rm keV})\ \Gamma_{10}$.

The profile of such a line may be mainly broadened by the relative motion among the cold clouds. As argued by Celotti et al. (1998), the strength of a comoving magnetic field is of typical value $B = 2\times10^3 L_{\rm jet,46}^{1/2} R_{15}^{-1}\Gamma_{10}^{-1}$ Gauss, where $L_{\rm jet,46} = L_{\rm jet}/10^{46}$ erg s^{-1} is the power of the jet as Poynting flux. Such a magnetic field can confine the relative motion among the cold clouds with respect to the relativistic bulk flow, otherwise the collimation of the jet will be broken down. This random velocity of the clouds υ_c can be estimated by $\frac{1}{2} n_t m_p \upsilon_c^2 = B^2/8\pi$. For the typical value, we have $\upsilon_c/c = 1.5\times10^{-3}$, namely, $\Delta E \approx \Gamma E_{K\alpha}\upsilon_c/c \approx 0.1\Gamma_{10}$ keV. If the thermal clouds follow the opening angle of the jet due to random motion, on the other hand, their relative velocity would be of order of $\upsilon_c/c \approx 0.1\Gamma_{10}^{-1}$. This causes a broadening of $\Delta E \approx 6.4$ keV. The resolution of the line profile may probe more detail dynamics of the jet in future.

From Eq. (7), we see that the observed line luminosity is very sensitive to the Lorentz factor Γ and proportional to the iron abundance $\mathcal{A}$. We use the maximum number of cold clouds (see Eq. (1)), the predicted luminosity of the iron Kα line is the upper limit. This limit is due to the absence of features of bulk Comptonization in the soft X-ray band. We note that the above model only works within BLR (~0.1pc).

2.3. Candidate objects with a blue-shifted Kα line

The proposed model naturally relates to the γ-ray emission model advocated by Sikora et al. (1994). $L_\gamma/L_{\rm syn} \approx U_{\rm UV}^{\rm ref}/U_B$ and $U_{\rm UV}^{\rm ref} > U_{\rm syn}$ implies that $L_\gamma/L_{\rm syn} > 1$ if the equipartition between magnetic field and relativistic electrons $U_B = U_e$ is fulfilled. Here L_γ is the γ-ray luminosity, $L_{\rm syn}$ is the luminosity due to synchrotron emission, U_B and $U_{\rm UV}^{\rm ref}$ are the energy densities of the magnetic field and of the reflected UV luminosity, respectively. *CGRO* observations of γ-rays from blazars show the importance of reflection (Dondi & Ghisellini 1995). The potential candidates for a blue-shifted iron Kα line should be those objects in which $L_\gamma/L_{\rm syn} > 1$. On the other hand the present model needs metal-rich thermal matter. This condition corresponds to the observable indicator of metallicity as N V/C IV $\geq$ 0.4 (Hamann & Ferland 1999). We thus have the criteria for potential candidates as

$$\frac{L_\gamma}{L_{\rm syn}} > 1; \quad \frac{\rm N\ V}{\rm C\ IV} \geq 0.4. \quad (8)$$

These conditions are likely satisfied in flat spectrum radio quasars. The superluminal motion of γ-ray bright blazars show that $\Gamma \sim 10$ is common among the γ-ray loud AGNs (Jorstad et al. 2001). In the sample of Dondi & Ghisellini (1995), the mean ratio of $L_\gamma/L_{\rm op} \approx 30$. We expect that the highly Doppler-shifted Kα line appears in most of these objects with high flux ratio N V/C IV in the sample of Dondi & Ghisellini (1995).

3. A predicted blue-shifted Kα line in 3C 273

3C 273 is a typical blazar with strong emission lines, powerful continuum emission from radio to γ-rays (see an extensive review of Courvoisier 1998). A very strong MeV bump has been discovered in 3C 273 by the *Compton Gamma-ray Observatory* (Lichti et al. 1995). This MeV feature could be explained by several different models, for example, a break in the electron injection function (Ghisellini et al. 1996), incomplete cooling of relativistic electrons (Sikora et al. 1994); and pair cascade process (Blandford & Levinson 1995). However, in such models, one encounters other difficulties to reconcile the broad band multi-wavelength continuum emission (see a brief review of Sikora et al. 1997). As argued by Sikora et al. (1997), the MeV feature could be explained naturally by the "hot electrons" version of the external radiation Compton model (Sikora et al. 1994) provided the plasma is not dominated by pairs. The future detection of the highly blue-shifted Kα line could help clarify the composition of the relativistic jet in radio-loud quasars.

The mass of the black hole in 3C 273 can be estimated from the absolute magnitude M_R of its host galaxy via $\log M_{\rm BH}/M_\odot = -0.5M_R - 2.96$, $M_{\rm BH} = 1.2\times10^9\ M_\odot$ from $M_R = -24.4$ (McLure & Dunlop 2001). The accretion rate of the black hole can be roughly estimated from the big blue bump (Walter et al. 1994; Wang & Zhou 1996). We find $\dot{m} \approx 0.4$, about half the Eddington luminosity, similar to Courvoisier (1998). The metallicity can be estimated through the flux ratio of N V/C IV (Hamann & Ferland 1999). The observed flux ratio of N V/C IV is 0.46 in 3C 273 (Baldwin et al. 1989), which gives a metal abundance $\mathcal{A} = Z/Z_\odot \approx 10$ from Fig. 6 of Hamann & Ferland (1999). The superluminal motion has been extensively studied, the latest observation

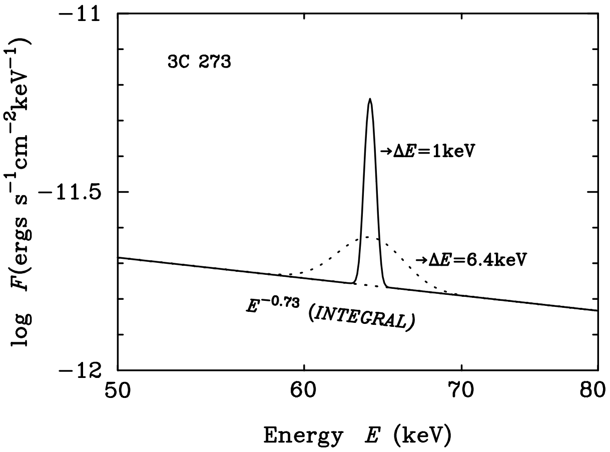

Fig. 1. A plot of the line profiles with future missions. A Gaussian profile for the line is assumed in the jet comoving frame. We assume two cases with energy resolution of $\Delta E = 1$ keV and $\Delta E = 6.4$ keV, respectively. The underlying continuum is the *INTEGRAL* spectrum observed by Courvoisier et al. (2003).

shows that the apparent velocities for different components are from $9c$ to $22c$ (Jorstad et al. 2001). Here, we take $\Gamma \approx 10$.

For the parameters of 3C 273, we estimate a Kα line luminosity $L_{K\alpha}^{\rm obs} \approx 3.0 \times 10^{44}$ erg s^{-1} and the flux $F_{K\alpha} = 3.9 \times 10^{-12}$ erg cm^{-2} s^{-1}. For the equivalent width, we use the *INTEGRAL* continuum spectrum, $F_E = 3.6 \times 10^{-11} E^{-0.73}$ erg cm^{-2} s^{-1} keV^{-1} (Courvoisier et al. 2003). The equivalent width is given by $EW(K\alpha) \approx F_{K\alpha}/F_E \approx 2.4$ (keV).

Using the observed background level for *SPI*, both analytical calculations as well as Monte Carlo simulations show that *SPI* will not be able to detect such a line in a total observing time of one million seconds. Figure 1 shows that for a next generation instrument for which we assume a 1 keV energy resolution a signal to noise ratio of $\sim$1–3 per resolution element is necessary in order to detect the line. This represents an improvement by a factor of $3 \sim 4$ on the presently available data that we expect will be available in missions like *NeXT* (New X-ray Telescope, Takahashi et al. 2004) and *XEUS* (X-ray Evolving Universe Spectrometer). The line profile for a well-collimated jet with the maximum width ($\Delta E = 6.4$ keV) discussed in Sect. 2.2 is also plotted in Fig. 1.

4. Conclusions

We show that future instruments may allow us to detect a thermal line emitted by matter in a jet directed towards us and therefore shifted to the blue by a factor that reflects the gamma factor of the jet. This would allow a direct measurement of the jet gamma factor and give very important indications on the as of yet not clear nature of the jet. The line flux is determined by 3 factors: the ionization level, the Lorentz factor and the metal abundance. Using realistic values for these parameters, we show that the next generation hard X-ray instruments may well measure this component.

Acknowledgements. The authors are grateful to the anonymous referee for pointing out an error in the early version of the paper and the helpful comments significantly improving the manuscript. They thank M. Stuhlinger for useful discussions and V. Beckmann for performing SPI simulations. H. Netzer is greatly thanked for helpful suggestions. J.-M.W. acknowledges support from the Alexander von Humboldt Foundation, NSFC and the Special Funds for Major State Basic Research Project.

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