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Detectability of x-ray absorption lines in quasar spectra

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In quasar x-ray spectra it may be feasible to detect absorption features originating in hot plasma in objects that happen to lie along the line of sight. For typical parameters of the hot plasma in rich galaxy clusters and in giant-galaxy halos, such x-ray lines in the spectra of distant ordinary quasars should have an energy equivalent width under 50 eV; for them to be detectable the sensitivity of existing instruments should be improved by at least an order of magnitude. The most promising transitions in abundant heavy elements are pointed out; in certain cases they might well be sought even now with the x-ray telescope carried by the Einstein Observatory.

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1. INTRODUCTION

Everyone realizes what a wealth of information is furnished by the optical and ultraviolet absorption lines in the spectra of stars, galaxies, quasars, and other astronomical objects. Now that observational x-ray astronomy is making rapid progress the question inevitably arises as to whether absorption lines might also be detectable in the x-ray range. Ions whose resonance transitions lie in the x-ray part of the spectrum will only occur in plasma at a sufficiently high temperature, $T > 10^6$°K. Since large complexes of hot gas containing hydrogen atoms with a column density $N_H l \geq 10^{20}$ cm^{-2} along the line of sight are observed in the central regions of rich galaxy clusters and might also be present in the halos of massive galaxies and quasars,[1] it seems to us that the most promising objects from the standpoint of detecting x-ray absorption lines are extragalactic x-ray sources — in particular, quasars.

X rays have been recorded from 50 quasars since the Einstein X-Ray Observatory (HEAO 2) was launched[2]; they have redshifts between 0.044 and 3.2. No doubt the number of these objects will grow considerably in the future. In the 0.5-4.5 keV energy interval their flux density ranges from a threshold of $\approx 10^{-14}$ to $\approx 10^{-10}$ erg $\cdot$ cm$^{-2}\cdot$ sec^{-1}. Quasar x-ray spectra have a distinctive feature: a weak cutoff in the soft region (or none at all), suggesting that a relatively small amount of neutral gas (column density[2] $N_H l < 10^{21}$ cm^{-2}) is present along the line of sight in the immediate vicinity of the quasars themselves. (By contrast, the x-ray spectra of active galaxy nuclei often show a steep falloff at energies $h\nu \le$ 1 keV, and the $N_H l$ values[3] reach $\approx 10^{23}$ cm^{-2}.) In view of this circumstance quasars may serve as convenient sources of x rays for studying the absorption in various objects that happen to lie on the line of sight. Thus far the only information on objects of this kind comes from absorption lines in the optical part of the spectrum.[4] In this paper we discuss the possibility of extending the absorption-line technique to the x-ray range.

2. EQUIVALENT WIDTH

Two limiting cases should be distinguished for the geometry of the absorbing cloud: a) the cloud is distant from the quasar, at which it subtends only a small solid angle; b) the cloud surrounds the quasar on all sides, covering a full solid angle of $\approx 4\pi$. In case (a) it is a simple matter to estimate the characteristics of an absorption line, because all the photons that have undergone resonance scattering will be missing from the flux that reaches the observer. In case (b) the photons which have experienced scattering along the line of sight will largely be compensated by photons scattered in other parts of the cloud. If the optical depth τ_0 of the cloud at the center of the line is much smaller than the thermalization length τ_{th}, the compensation will be nearly complete. All the estimates given below will refer to the simpler case (a). We thereby exclude from consideration any gas located in the immediate environment of the radiating quasar. One should keep in mind, however, that even in case (b) absorption lines might in principle be observable if, for example, the gaseous envelope around the quasar is highly inhomogeneous.

Let us now estimate the optical depth at the center of the absorption line as well as its equivalent width. We shall assume that the line has a Doppler profile. That will surely be the case for thermal motion at the low densities that may be expected in the interstellar, and even more so the intergalactic, gas. For want of a better hypothesis we shall suppose that the macroscopic velocities of the separate parts of the cloud also have a Gaussian distribution.

Let $\langle v^2 \rangle$ denote the combined dispersion of the thermal and macroscopic velocities. The expression for the resonance-absorption cross section at the center of a line corresponding to photons of energy $\varepsilon = \varepsilon_0$ may be written in the form

$$\sigma_0 = \frac{1}{\sqrt{\pi}\,\varepsilon_0(\bar{v}/c)} \int_{-\infty}^{+\infty} \sigma(\varepsilon)\,d\varepsilon = \frac{2\pi^{3/2} e^2 \hbar}{m_e c} \frac{f_{12}}{\varepsilon_0(\bar{v}/c)}, \qquad (1)$$

where $\bar{v} = \langle v^2 \rangle^{1/2}$ and f_{12} is the oscillator strength of the resonance transition. The optical depth at the line center will be

$$\tau_0 = \sigma_0 x X N_H l = 1.9\cdot 10^{17} x X f_{12} N_H l \left(\frac{1000\ \text{km/sec}}{\bar{v}}\right)\left(\frac{1\ \text{keV}}{\varepsilon_0}\right), \qquad (2)$$

where x denotes the degree of ionization, X is the abundance relative to hydrogen of the element responsible for the resonance line, and $N_H l$ is the number of hydrogen atoms (and ions) along the line of sight. The equivalent width W of the line is given in terms of τ_0 by the simple expression

$$W = \sqrt{\pi}\left(\frac{\bar{v}}{c}\right)\varepsilon_0 \varphi(\tau_0), \qquad (3)$$

where the function $\varphi(\tau_0)$ has the form

$$\varphi(\tau_0) = \begin{cases} \tau_0, & \tau < 1, \\ 2\sqrt{\ln \tau_0}, & \tau_0 \gg 1. \end{cases} \qquad (4)$$

Equation (3) is convenient for estimating the maximum possible equivalent width of a resonance line at energy ε_0. In view of the definition (4) one may simply set $\varphi_{max}(\tau_0) \approx$ 1-3; then

$$W_{max} \le 20\left(\frac{\bar{v}}{1000\ \text{km/sec}}\right)\left(\frac{\varepsilon}{1\ \text{keV}}\right)\ \text{eV}. \qquad (5)$$

3. PARTICULAR TRANSITIONS

Equation (2) shows that the transitions of greatest observational interest are strong ones ($f_{12} \sim 1$) in the

TABLE I. Quasars Observable Behind Clusters

QSO	z	m_V	Cluster	z	Richness
1258+287	0.65	18	A 1656 (Coma Cl)	0.388	2
1258+286	1.92	17.7			
1258+286	1.37	19			
0726+431	1.07	18.5	A 583	0.179	2
1606+180	0.35	18	A 2151	0.036	2
1559+173	1.94	18			
0024+22	1.12	16.6	A 31	0.16	2

TABLE II. Paired Quasars

QSO	z	Δθ	Δl, Mpc	Δv_0, km/sec*
0147+090 0148+090	0.27 0.30	1′	0.35	~6900
0254−334 0254−334	1.915 1.849	5″.0	0.04	~6900
0957+561 A 0957+561 B	1.4 1.4	5″.7	0.01	≤100
1548+115 1548+115	0.436 1.9	4″.8	0.04	In projection
1146+1104 1146+1106	1.01 1.01	2′.5	0.5	~450

*Velocity differential in quasar reference frame.

most abundant elements. Such lines may be divided into two main groups:

1. Hydrogenlike iron lines (Fe XXVI; $\varepsilon_0 = 6.97$, 6.95 keV) and heliumlike iron lines (Fe XXV; $\varepsilon_0 = 6.70$, 6.67 keV).

2. Lines of lithiumlike iron (Fe XXIV) and lower ionization stages of iron (down to Fe XVII; $\varepsilon_0 = 0.7$-1.2 keV), and lines of the hydrogen- and heliumlike ions of oxygen (O VIII, O VII; $\varepsilon_0 = 0.65$, 0.57 keV) and carbon (C VI, C V; $\varepsilon_0 = 0.37$, 0.31 keV).

The lines of other elements are of lesser interest because of the lower abundance of those elements but more detailed analysis might show that they could play some role, if only in controlling the temperature of the absorbing clouds.

On applying Jordan's ionization-equilibrium calculations[5,6] we see at once that the group 1 lines will be strong only if the absorbing gas is at a temperature $T \sim 10^8$°K. Temperatures of this order are typical of the central regions in clusters of galaxies.

However, the prospects of detecting the group 1 lines appear to be poorer than for the hydrogen- and heliumlike oxygen lines. The pertinent arguments here are:

a. Iron is normally an order of magnitude less abundant than oxygen, and a column density $N_H l \approx 10^{21}$ [(1000 km/sec)/$\bar{v}$] cm^{-2} would be required to achieve an optical depth $\tau_0 \approx 1$.

b. Beyond the central regions of rich clusters, the only place where such high $N_H l$ values can be expected, a quasar is likely to be detected only if its redshift $z > 1$, and its x-ray intensity would then be weak. In the case of Einstein Observatory, in order for the group 1 lines to have fallen within the 0.5-4.5 keV passband of its instruments the clusters themselves would have had to lie at distances corresponding to $z \gtrsim 1.5$, thereby even further impairing the chances of observing such absorption lines.

Among the group 2 lines the iron lines will be strongest if $T \approx 10^7$°K, while the oxygen and carbon lines will predominate if $T \approx 10^6$°K. Temperatures of this order may be anticipated in the gaseous halos presumed to surround giant galaxies and quasars. And since these x-ray lines would come within the Einstein passband for redshifts $z \approx 1.0$, they might, in principle, already have been recorded in the spectra of bright quasars.

The most attractive lines for our purpose are the resonance lines (the $1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$ transition) of heliumlike oxygen and carbon ions, for which the factor xXf_{12} may reach values of $\approx 5 \cdot 10^{-4}$, and which would become fairly strong even for values $N_H l \approx 10^{20}$ [$\bar{v}$/(1000 km/sec)] cm^{-2}. Another favorable property of these lines is the fact that at suitable temperatures the relative abundance of helium-like ions should be of order unity,[5] so that for each element the spectrum will contain one deep absorption line. In the case of lithiumlike and lower ions of iron, on the contrary, several ions will always be present at any temperature with comparable relative abundances.[6] Each of these ions will have several transitions of roughly the same strength, and as a result iron will display a comb of, say, 10 absorption lines in the energy interval (0.7-1.2 keV)/(1 + z); their combined equivalent width, as a rule, will be no more than a few tens of electron volts.

It is also worth noting that along with resonance absorption lines the x-ray spectrum should contain absorption "jumps" on the short-wave sides of the lines, corresponding to series limits. The cross section for bound–free absorption at a series limit will be smaller than the cross section at the center of a line; in the case of the O VIII and O VII ions the optical depth $\tau < 1$ at the series limit if $N_H l < (0.3$-$1) \cdot 10^{22}$ cm^{-2}. The equivalent width of the absorption jump can then be estimated from Eqs. (3), (4) for $\tau_0 < 1$. It turns out to be comparable with the equivalent width of the corresponding resonance absorption lines, since the sum of the oscillator strengths of the bound–free transitions is nearly equal to the oscillator strength f_{12} of the resonance transition (0.409 or 0.416 for the hydrogenlike ions). It would, however, be harder to observe the absorption jumps than narrow lines, as they would be considerably broader: $\Delta\nu \sim \nu$.

4. DETECTION PROSPECTS

The outstanding examples of objects in which x-ray absorption lines might develop are clusters of galaxies. At present it is reliably established that the central regions ($r < 500$ kpc) of rich clusters contain hot gas at a temperature $T \approx 10^7$-10^8°K, for which the column density $N_H l$ may reach values of order 10^{21} cm^{-2} (see, for instance, Sarazin and Bahcall).[7] Clusters having $T \approx 10^8$°K ought to give rise to iron lines of energy $h\nu \approx (6.7$-7.0 keV$)/(1+z)$, while at lower temperatures ($T \approx 10^7$°K) we should observe lines of lithiumlike and lower iron ions. Table I lists some examples of rich clusters and quasars located beyond them. Also of interest are certain cases of nearby quasars situated inside galaxy clusters.[8]

As another place where a substantial amount of hot ($T \approx 10^6$-10^7°K) gas may be collected, one may turn to the halos of giant spheroidal systems. In the case of such nearby galaxies as M87, Centaurus A, and Perseus A, the presence of a gaseous halo is confirmed by soft x-ray observations.[9,10] The average gas density in halos is $n_H \approx 10^{-2}$ cm^{-3}, and $N_H l$ may reach values of $\approx 3 \cdot 10^{20}$ cm^{-2}. Conceivably halos of this kind, if not even more powerful ones, may also surround certain quasars. It might accordingly be of some interest to search for x-ray absorption lines in the spectra of "paired" quasars, in contiguous positions on the celestial sphere. Some examples of such pairs are given in Table II. Among these we would single out the pair 0957 + 561 A, B, which purportedly[11] is located beyond a cluster of galaxies having $z \approx 0.4$. X-ray observations of this pair would be particularly worthwhile. Another interesting case is the group of quasars[12] near $\alpha = 11^h46^m$, $\delta = 11°04'$.

The gas in clusters and halos of galaxies would hardly be expected to have velocity dispersions $\bar{v} > 3000$ km/sec. We may at once infer from the condition (5) that the equivalent width of, say, the O VII lines cannot exceed 30 eV. And the line would be narrow: $\Delta\varepsilon/\varepsilon \leq 10^{-2}$. For a flux density $F_{XR} = 3 \cdot 10^{-12}$ erg$\cdot$cm$^{-2}\cdot$sec^{-1} in the 0.5-4.5 keV range (only three quasars are known whose intensity in this interval exceeds 10^{-11} erg$\cdot$cm$^{-2}\cdot$sec^{-1}) and a spectrum of slope[2] $\beta = 1$, the deficiency of photons in the line will be

$$N_{\tau} \simeq \frac{F_{xR} W}{(4.5\ \text{keV} \ -0.5\ \text{keV}\ )\,\varepsilon_0} \leqslant (0.3-1)\cdot 10^{-5} \left(\frac{\bar{v}}{1000\ \text{km/sec}}\right) \frac{\text{photons}}{\text{cm}^2\cdot\text{sec}}. \quad (6)$$

This limit is about two orders of magnitude below the sensitivity of the instruments aboard the Einstein Observatory.

We conclude, then, that in order to develop a broad-scale observing program for the study of x-ray absorption lines in quasar spectra it will be necessary to improve the spectral sensitivity of currently available instrumentation by at least two orders of magnitude.

Nevertheless, we would not rule out the possibility that exotic situations might exist in which the photon deficiency in an absorption line may become anomalously great. For example, if the line of sight should cross a powerful gas jet with a velocity dispersion $\bar{v} \approx 100{,}000$ km/sec and $N_H l \approx 10^{22}\ \text{cm}^{-2}$, then x-ray absorption lines might be detectable even by techniques at hand today. Situations of this kind would most likely be encountered in cases where the quasar spectrum displays either exceptionally broad absorption features (such as the spectrum of PHL 5200; see, for example, Clowes el. al.[13]) or a "superluminal" separation of the components of nuclear radio sources (as in the quasar 3C 273).

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Note added in proof. After this paper was sent to press an analysis of the problem by Shapiro and Bahcall[14] was received; these authors' conclusions regarding the intensity of x-ray absorption lines in quasar spectra are consistent with ours.

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