The 6.4 keV Fluorescent Iron Line from Cluster Cooling Flows

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ABSTRACT
The fate of the cooling gas in the central regions of rich clusters of galaxies is not well understood. In one plausible scenario clouds of atomic or molecular gas are formed. However the mass of the cold gas, inferred from measurements of low energy X-ray absorption, is hardly consistent with the absence of powerful CO or 21 cm lines emission from the cooling flow region. Among the factors which may affect the detectability of the cold clouds are their optical depth, shape and covering fraction. Thus, alternative methods to determine the mass in cold clouds, which are less sensitive to these parameters are important.

For the inner region of the cooling flow (e.g. within the radius of ∼50–100 kpc) the Thomson optical depth of the hot gas in a massive cooling flow can be as large as ~ 0.01. Assuming that the cooling time in the inner region is few times shorter than the life time of the cluster, the Thomson depth of the accumulated cold gas can be higher accordingly (if most of the gas remains in the form of clouds). The illumination of the cold clouds by the X-ray emission of the hot gas should lead to the appearance of a 6.4 keV iron fluorescent line, with an equivalent width proportional to τ_T. The equivalent width only weakly depends on the detailed properties of the clouds, e.g. on the column density of individual clouds, as long as the column density is less than few $10^{23}\ cm^{-2}$. Another effect also associated exclusively with the cold gas is a flux in the Compton shoulder of bright X-ray emission lines. It also scales linearly with the Thomson optical depth of the cold gas. With the new generation of X–ray telescopes, combining large effective area and high spectral resolution, the mass of the cold gas in cooling flows (and it's distribution) can be measured.

Key words: galaxies: clusters: general – cooling flow – intergalactic medium – X-rays: galaxies.

1 INTRODUCTION

The radiative cooling time of the gas in the central parts of rich clusters of galaxies can be considerably shorter than the Hubble time (Lea et al. 1973; Silk 1976; Cowie and Binney 1977; Fabian and Nulsen 1977) and the gas may cool down below X–ray temperatures, forming a cooling flow (see Fabian, 1994 for review). Strong peaks in the surface brightness distribution, observed in many clusters of galaxies (e.g. Branduardi–Raymont et al. 1981, Fabian et al. 1981, Canizares, Stewart & Fabian A.C. 1983, Fabricant & Gorenstein 1983, Jones & Forman 1984, Stewart et al. 1984), are usually considered as indicators of a cooling flow. Evidence for cool gas was also found in the spectroscopic observations, which revealed the presence of emission lines, characteristic of gas with the $T_e \leq 5 \times 10^6$ K gas (e.g. Canizares et al., 1979). Detailed studies of the surface brightness distribution in the cooling flows lead to the conclusion, that a fraction of the gas drops out from the flow at different radii, such that the mass deposition rate is proportional to the radius: $\dot{M}(< R) \propto R$ (e.g. Thomas, Fabian and Nulsen, 1987). The fate of the gas which has dropped out from the flow is not well understood. Only small fraction of the cooling gas can form stars with a normal IMF. The optical and UV observations of the central galaxy restrict the total rate of massive star formation rate typically by $\sim$ 5–30 $M_\odot/year$ (e.g. Fabian et al. 1984, McNamara & O'Connel 1993, Cardiel, Gorgas, Aragon-Salamanca 1995, Smith et al. 1997). Detection of excess absorption in several cooling flow clusters (e.g. White et al., 1991) seems to support the hypothesis that the cooling matter forms clouds of atomic or molecular gas. To provide effective absorption, cold clouds must have a covering fraction close to unity (White et al. 1991). Recent analysis by Allen and Fabian (1997) of a sample of nearby cooling flow clusters observed with ROSAT confirmed presence of excess absorption, although with covering fraction somewhat lower than unity. The derived masses of X–ray–absorbing material are $\sim 10^{12}\ M_\odot$ (White et al. 1991) and are hardly consistent with the absence of powerful CO and HI emission (e.g. O'Dea et al. 1994, Voit and Donahue 1995). Thus, independent determinations of the cold gas mass are important in understanding the fate of the cooling gas. Geometrically small, optically thick clouds may easily escape detection. Therefore observations at the wavelengths at which the clouds are transparent are the best indicators of total mass of cold gas. From this point of view, X–rays with energies above ∼6 keV could be useful, since clouds only become opaque at these energies when hydrogen column density exceeds few 10^{23}–$10^{24}\ cm^{-2}$.

The Thomson depth of the cooling flow regions, calculated for the hot X–ray emitting gas, can be of the order of 0.01. Assuming a cooling time in the inner region which is few times shorter than the Hubble time, the averaged Thomson depth of the gas deposited during the life time of the cluster can be even higher. We argue below that such an amount of cold gas is sufficient to produce the emission from the 6.4 keV fluorescent iron line with a flux well above the sensitivity limit of future X-ray missions. Possible presence of the 6.4 keV line in clusters was also noted earlier by Vainshtein & Sunyaev (1980) and White et al. (1991). Another effect, associated with cold gas, which also might be observed for such values of Thomson optical depth is the Compton shoulder of the brightest X–ray emission lines. Note that (unlike CO and 21 cm lines or low energy absorption) the fluxes in the 6.4 keV line and Compton shoulder do not depend strongly on the shape or column density N_H of the individual cold clouds as long as N_H is lower than $\sim 10^{24}\ cm^{-2}$.

2 EQUIVALENT WIDTH OF THE 6.4 KEV LINE

Let us consider the simplest case of a uniform sphere of neutral (or molecular) gas with an X–ray continuum source at the center. We assume that the optical depth of the sphere is less than 1 for X–rays above ∼ 6 keV. Absorption of the X–ray photons above the iron K–shell absorption edge (E_K = 7.1 keV) will cause (with probability $Y \sim 0.3$, e.g. Bambinek et al., 1972) emission of 6.4 keV photons. Thus, the equivalent width of the 6.4 keV line for the whole region can be calculated as (e.g. Vainshtein & Sunyaev, 1980):

$$EW = \frac{Y N_H A_{Fe} \int_{E_K}^{\infty} \sigma_{Fe}(E) I(E) dE}{I(6.4)} \qquad (1)$$

where N_H is the hydrogen column density of the region, A_{Fe} is the iron abundance relative to hydrogen (we adopt $A_{Fe} = 4.68\ 10^{-5}$, Anders and Grevesse, 1989), $\sigma_{Fe}(E) = 3.5 \times 10^{-20} (E_K/E)^{2.8}\ cm^2$ is the photoabsorption cross section (from the K shell) of an iron atom, $I(E)$ is the incident X-ray spectrum (in $phot/s/sm^2/keV$). One can rewrite equation (1) in a more convenient form:

$$EW = 0.74 \left(\frac{A_{Fe}}{4.68\ 10^{-5}}\right) \frac{\int_{E_K}^{\infty} (E_K/E)^{2.8} I(E) dE}{I(6.4)} \tau_T\ keV \qquad (2)$$

For hard power law spectra, the equivalent width of the 6.4 keV line can be of the order of τ_T keV. In the cooling flow region, X–ray emission of the gas is relatively soft and equivalent width may be lower (see however next section). We calculated the expected equivalent width assuming, for $I(E)$, an emission spectrum of an optically thin plasma at different temperatures (Table 1)⋆. Table 1 shows that although "hotter" spectra have a clear advantage in terms of producing a larger equivalent width of the iron line, this temperature dependence is not too steep and a change of temperature from 10 to 1 keV results in a decrease by only a factor of ∼ 4 in the equivalent width.

Table 1. Equivalent width of the 6.4 keV iron fluorescent line, calculated assuming an emission spectrum of optically thin plasma at different temperatures, and normalized to unit Thomson optical depth and solar abundance of iron (see equation 2)

Temperature (keV)	EW (keV) $0.74\ \frac{\int_{E_K}^{\infty} (E_K/E)^{2.8} I(E) dE}{I(6.4)}$
1	0.24
2	0.54
3	0.71
4	0.83
10	1.09

3 THOMSON DEPTH OF THE COOLING FLOW REGION

To estimate the expected equivalent width one should multiply the value, given in Table 1, by the Thomson depth of the region and the iron abundance relative to the solar value. Assuming that all gas, deposited in a cooling flow during a Hubble time $t_H \sim 2 \times 10^{10}$ years, forms clouds of neutral gas, one can write:

$$\tau_T = 1.7 \times 10^{-2} \left(\frac{R}{50kpc}\right)^{-2} \left(\frac{\dot{M}}{100 M_\odot/year}\right) \qquad (3)$$

The above estimate assumes that the cold gas is uniformly distributed over the volume and the source of continuum radiation lies at the center. Multiplying eq.(3) by the factor from Table 1 (e.g. for T_e = 3 keV see also discussion below) one can write for a final estimate of the equivalent width:

$$EW \sim 12 \left(\frac{R}{50kpc}\right)^{-2} \left(\frac{\dot{M}}{100 M_\odot/year}\right) \left(\frac{A_{Fe}}{4.68\ 10^{-5}}\right)\ eV \qquad (4)$$

⋆ Here and in the subsequent sections we used MEKA model (Mewe, Gronenschild & van den Oord 1985; Mewe, Lemen & van den Oord 1985; Kaastra 1992) as implemented in XSPEC v10 (Arnaud 1996) to simulate thermal emission from an optically thin plasma.

Note that although the hot gas in clusters has (on average) an iron abundance less than solar (~ 0.3–0.5), a central concentrations of heavy elements was observed in a number of clusters with cooling flows (e.g. Fukazawa et al., 1994). Note also that the above estimate is insensitive to the shape of the clouds. As long as each individual cloud has an optical depth (for Thomson scattering and for photoabsorption above 6 keV) much less than 1, a clumpy distribution (with an arbitrary covering fraction) will result in the same equivalent width as a uniform distribution. The radial distribution of the scattering medium is more important.

4 DISCUSSION

4.1 6.4 keV line

Let us consider the case of an isothermal cluster, i.e. whose emission spectrum at any place in the cluster is characterized by the same value of temperature T_e. Assuming that the mass deposition rate is proportional to the radius (e.g. Thomas, Fabian and Nulsen, 1987), one can see that the most favorable conditions for producing 6.4 keV fluorescent iron emission is in the very center of the cooling flow. Since the surface brightness of cooling flow clusters is very strongly peaked, then the emission from this region may dominate the spectrum even if the spatial resolution of the instrument does not allow one to fully spatially resolve the cooling flow region. The equivalent width of the 6.4 keV line reflects the total mass of iron in the region and is insensitive to the shape or size of the clumps, as long as each individual clump is optically thin for X–rays above 6 keV. On the other hand, the same clouds can be optically thick to low energy X–rays and the efficiency of low energy absorption can be low (recalculated per hydrogen atom). Thus, if clumps are dense and have a small covering fraction†, they may not contribute significantly to the low energy absorption, but still effectively produce 6.4 keV photons. Note also, that the resulting equivalent width is almost insensitive to the temperature of the clumps, as long as the temperature is low enough.

Allen et al. (1996) identified three distant clusters: Zwicky 3146 ($z = 0.291$), Abell 1835 ($z = 0.252$) and E1455+223 as having the largest known mass deposition rates of 1400, 2300 and 1500 $M_\odot/year$. The equivalent width of the line from these clusters can be of the order of tens of eV. For nearby clusters, A478 ($z = 0.09$), has a large mass deposition rate of order 1000 $M_\odot/year$ at $R \sim 200$ kpc (Allen et al., 1993) and the equivalent width within the 100 kpc central region may be of the order of 10 eV. One can make a "more accurate" estimate of the equivalent width for this cluster (Fig.1), using the results of the deprojection analysis by Allen et al., 1993 and White et al., 1994. Shown in the bottom panel of Fig.1 is the expected equivalent width of the 6.4 keV line, calculated as a function of the projected radius from the cluster center. In these calculations we assumed that the gas in the cluster is isothermal

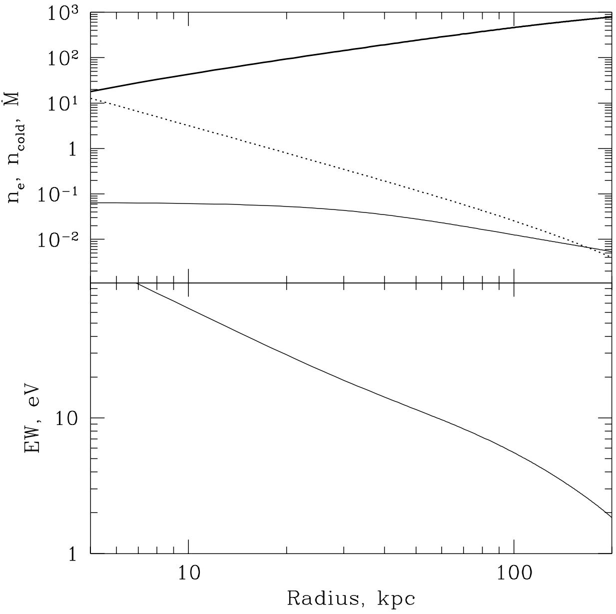

Figure 1. Upper panel: The assumed radial distributions of hot gas density $n_e(r)$ in cm^{-3} (thin solid line), mass deposition rate in $M_\odot$ per year (thick solid line) and the density of cold gas $n_{cold}(r)$ in cm^{-3} (dashed line) accumulated for 2×10^{10} years. **Lower panel:** The equivalent width of the 6.4 keV line as a function of the projected distance R from the center. For this figure we adopted the results on $n_e(r)$ and $\dot{M}$ of White et al. 1994.

with a temperature of $T_e \sim 3$ keV (Allen et al., 1993). Of course, given the lack of knowledge of what is the real fate and distribution of the cooling gas, these calculations may not provide more accurate estimates of the line flux than the simple estimates in the previous section for the region as a whole (assuming a uniform distribution of the cold gas).

The total flux in the fluorescent line is defined by the quantity $n_{cold}(r) \times \int_{E_K}^{\infty} (E_K/E)^{2.8} \mathcal{E}(E,r) dE$ (where $n_{cold}(r)$ is the density of cold gas and $\mathcal{E}(E,r)$ is the radiation density) integrated over the volume occupied by the cold gas. Note that only that part of the radiation density spectrum above 6 keV determines the flux and equivalent width of the line. Although the emission measure weighted temperature is low in the cooling flow region, compared to the outer hot regions, it is likely that cooling flows are inhomogeneous and hot gas is present even at small radii (e.g. Fabian and Nulsen, 1977, Nulsen 1986, see Fabian, 1994 for review) and above 6 keV the contribution to the radiation density from this hot phase may be dominant (see e.g. Allen, Fabian & Kneib 1996). One can estimate the "effective" temperature, i.e. the value of T_e which should be used for calculating the line flux (see Table 1), using the high energy (above 6 keV) part of the observed spectrum towards the center of the cluster, since the shape of the radiation density spectrum at the cluster center and the observed spectrum along this line of sight coincide for a symmetric cluster. Note also, that if an AGN (having hard X–ray spectrum) is present in the nucleus of the central

† Discussion of the constraints on the cloud parameters, which can be derived considering in detail conditions in the cooling region(see e.g. Daines, Fabian and Thomas 1994) are beyond the scope of this article.

galaxy, then the equivalent width of the fluorescent line will be appropriately higher.

Assuming that the trend $M_\odot \propto R$ holds down to small radii and cold clouds remain in the region, where they were deposited, then equivalent width will be highest in the very central region of the cooling flow. As noted above if the radiation density (above 6 keV) is strongly peaked at the center of the cooling flow then the emission measure weighted equivalent width from the whole region (within given radius) can correspondingly be higher than the equivalent width calculated for given projection radius.

With present instruments (e.g. ASCA) the detection of the 6.4 keV line from the cooling flow regions is questionable. The expected flux in the 6.4 keV line is relatively weak compared to that of the 6.7 keV line complex and the combination of energy (and angular) resolution and sensitivity may not be sufficient to detect $EW \sim 10$ eV features from clusters. The better energy resolution of ASTRO-E (with bolometers), Spectrum–X–Gamma with the Bragg spectrometer – OXS (see e.g. Christensen et al. 1990) and especially CONSTELLATION/HTXS (White, Tananbaum & Kahn 1997) will allow one to detect this line from the clusters with massive cooling flows (if most of the cooling gas indeed forms molecular clouds). For Perseus (assuming an equivalent width of $\sim$ 10 eV) about 100 line photons could be detected in a 100 ksec observation with the Bragg spectrometer of Spectrum–X–Gamma. Shown in Fig.2 is the expected number of photons which will be detected from the central $2'$ region of the Perseus cluster. An effective area of $\sim$100 cm^2 (taking into account the peak reflectivity of $\sim$21%) and an energy resolution of $\sim$5 eV were assumed. The intrinsic structure of the 6.4 keV line (which consists of two components separated by $\sim$13 eV) was used to generate the figure. A few 100 ksec exposures (to measure line and continuum fluxes) should be sufficient to detect the 6.4 keV line with an equivalent width of a few eV. For the AXAF High Energy Transmission Grating extended nature of the source will significantly complicate the detection of the spectral features. CONSTELLATION with anticipated effective area of $\sim$ 6000 cm^{-2} and an energy resolution of few eV will be able to detect very weak lines during short exposure thus allowing studies of clusters with much weaker cooling flows. With CONSTELLATION it should be even possible to detect 6.4 keV line associated with column densities of the cold gas $\sim 10^{21}$ cm^{-2} derived from low energy absorption studies (White et al. 1991).

The part of the spectrum around the 6.4 keV line should be relatively free from contamination by bright emission lines from the hot gas. At temperatures lower than $\sim$ 1 keV, excitation of the inner shells of FeXVII–FeXX ions by electron impact may produce lines at 6.42–6.47 keV, but their equivalent widths should not be high, if the higher temperature components (above $T_e \sim 1$ keV) dominate the spectrum at energies of $\sim$ 6 keV.

Along with the 6.4 keV (K_α) line the K_β line at 7.06 keV should be present with intensity about 10 times lower ($\frac{17}{150}$) than that of the K_α line. The absorption edge at an energy of 7.1 keV should also be present. However it may be considerably more difficult to detect relatively wide absorption feature compared to emission line.

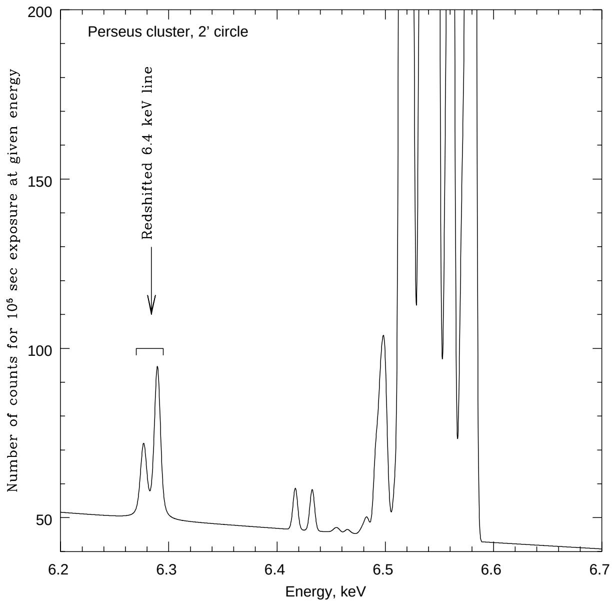

Figure 2. The number of photons, which could be detected by OXS of Spectrum–X–Gamma at a given energy during a 10^5 s exposure towards the Perseus cluster (central 2 arcmin circle). The value of 10 eV was adopted for the total equivalent width of the 6.4 keV line (which consists of two components). The energy resolution of the OXS is $\sim$ 5 eV.

4.2 Compton shoulder

Another effect, which also scales linearly with the Thomson depth of the cold gas is the Compton shoulder, associated with the brightest emission lines. Assuming a Thomson depth for the cold gas of $\tau_T \sim 0.1$ one can conclude that $\sim$ 10% of all photons (in particular, those in emission lines) will be scattered, forming the so-called Compton shoulder at the left (low energy) side of the emission lines (Fig. 3). Hot gas does not contribute to the formation of the Compton shoulder, since large thermal velocity of the electrons causes complete smearing of the features. On the other hand scattering of the emission lines by electrons bound in atoms and molecules will produce the Compton shoulder with distortions, specific to the given type of atom or molecule (Sunyaev & Churazov 1996). This effect is also weakly dependent on the cloud parameters and in principle provides the unique possibility of distinguishing between the contributions of free ($\sim$ cold) electrons, atomic hydrogen, atomic helium or singly ionized helium, although presence of blends of emission lines (like the 6.7 keV complex) may significantly complicates the measurements. In principle, combined measurements of the iron K_α line and the Compton shoulder allow one to determine the iron abundance ($\frac{Fe}{H}$) in the cooling flow.

5 CONCLUSIONS

Future X–ray missions, combining high energy resolution and large effective area, will be able to estimate the amount of cold gas deposited in massive cooling flows, by measur-

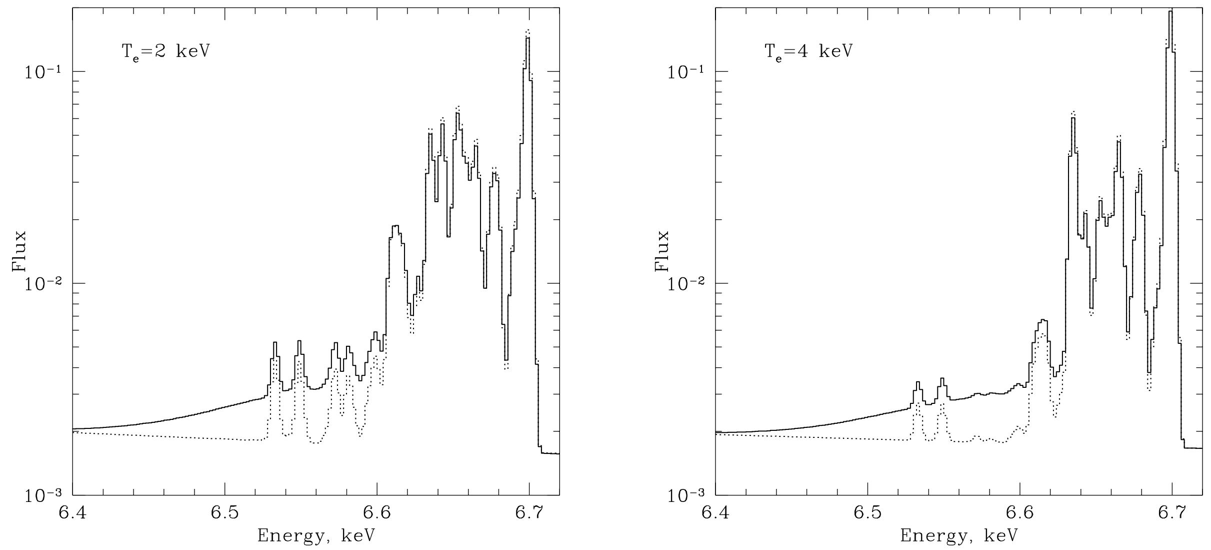

Figure 3. The dotted line shows the emission spectrum from an optically thin plasma (MEKA model as produced by XSPEC) at $T_e = 2$ keV (left) and $T_e = 4$ keV (right), convolved with a FWHM=5 eV Gaussian. Solid line shows the effect on the spectrum of scattering by neutral hydrogen (for a Thomson optical depth of 0.1). The scattered $\sim$ 6.6–6.7 keV photons have slightly lower energies, causing an increase in the continuum level at 6.5–6.6 keV by a factor $\sim 1.5 \times (\frac{\tau_T}{0.1})$). Note that in the presence of lower temperature components this 6.5–6.6 keV region may also be contaminated by weaker emission lines.

ing the equivalent width of the 6.4 keV iron fluorescent line or the intensity of the Compton shoulder, associated with brightest X–ray emission lines. Assuming that the bulk of the cooling gas forms cold molecular clouds, the expected fluxes are high enough to ensure their detection. These measurements could provide robust estimate of the gas mass, insensitive to the detailed shape, density or temperature of the cold clouds, as long as column densities of individual clouds are less than $\sim 10^{24}\ cm^{-2}$. In particular, the intensity of the 6.4 keV line will be less dependent on the covering fraction of the clouds than either the magnitude of the low energy absorption or the intensity of the 21 cm or CO lines, both of which are more sensitive to the column densities of individual clouds.

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