**Abstract.** X-ray spectra of a significant fraction of cooling flow (CF) clusters of galaxies indicate the presence of large columns of “cold” absorbing gas. The physical nature of the absorbing medium remains a mystery. Searches for H I absorption using the 21 cm hyperfine structure line yielded null results in most cases. The purpose of this contribution is to point out that the Lyman $\alpha$ absorption cross section is $\geq 10^7$ times larger than for the 21 cm line, it can therefore be used as a very sensitive probe of the H I column in clusters, and can thus place stringent constraints on the nature of the X-ray absorber. This method is applied to the Perseus CF cluster where a medium resolution ($\sim 250$ km s$^{-1}$) UV spectrum is available. The upper limit on the H I column obtained using Lyman $\alpha$ is at least $\sim 50$ times smaller than the 21 cm detection, and $\sim 5,000$ smaller than implied by X-ray spectra, indicating that the X-ray absorber is exceedingly devoid of H I. Higher resolution UV spectra with HST may improve the H I column limits by an additional factor of $\sim 4,000$. This method can be applied to strongly constrain the nature of the X-ray absorbing medium in a significant fraction of CF clusters.

1. Introduction

The presence of ubiquitous X-ray absorption in cooling flow (CF) clusters was first discovered by White et al. (1991) using the *Einstein* Solid State Spectrometer (SSS), and was later verified using *EXOSAT*, *ROSAT*, and *ASCA* (e.g. Allen et al. 1992; Fabian et al. 1994). The typical observed columns are a few $10^{20}$ to a few $10^{21}$ cm$^{-2}$. Searches were conducted at other wavelengths in order to verify the presence of the absorber and to understand its nature. Emission line constraints rule out absorbing gas at $T \sim 10^5 – 10^6$ K, and thus the absorbing gas must be mostly H I and/or H$_2$. Extensive searches for H I absorption using the 21 cm hyperfine structure line (e.g. Jaffe 1990; Dwarakanath, van Gorkom, & Owen 1994) and searches for CO associated with H$_2$ (e.g. O’dea et al. 1994; Antonucci & Barvainis 1994) yielded upper limits typically well below the X-ray columns. The 21 cm limits are linear with the electron excitation temperature, and may thus be subject to significant uncertainty.

For example, in the case of NGC 1275, the central galaxy in the Perseus CF cluster, the X-ray column obtained by the *Einstein* SSS is $1.3^{+0.3}_{-0.3} \times 10^{21}$ cm$^{-2}$ (White et al. 1991), by *EXOSAT* $1.5^{+2.1}_{-0.9} \times 10^{21}$ cm$^{-2}$ (Allen et al. 1991), and...
by ASCA 3 − 4 × 10^{21} \text{ cm}^{-2} (Fabian et al. 1994). The 21 cm line, however, indicates an H I column of only 2 × 10^{18}T_s \text{ cm}^{-2} (Jaffe 1990).

In this paper we show that significantly tighter limits on $N_{\text{H I}}$ can be obtained using Lyα. We first make a short comparison of the absorption properties of Lyα versus the 21 cm line. We then apply the results of curve of growth analysis for Lyα to show that the H I column $\sim 10 − 20$ kpc away from the center of NGC 1275 is significantly smaller than indicated by the 21 cm line, and demonstrate that improved limits can be obtained with a higher quality UV spectrum. We end with a short discussion of the implications of the new upper limits on $N_{\text{H I}}$ on the nature of the X-ray absorber.

2. On Lyman α vs. 21 cm Absorption

In this section we compare the absorption properties of Lyman α versus the 21 cm line. In a two level atom the absorption cross section per atom is:

$$\sigma_\nu = \frac{\pi e^2}{mc} f_{12} \phi(\nu) f_{se} \frac{n_1}{n_1 + n_2}$$

where $f_{12}$ is the oscillator strength, and $\phi(\nu)$ is the line profile function (Voigt function for pure thermal broadening). The parameter $f_{se}$ is the correction for stimulated emission given by

$$f_{se} = 1 - \frac{n_2 g_2}{n_1 g_1}$$

where $n_i, g_i$ are the population and degeneracy of level i. The level population is accurately described by the Boltzmann ratio since collisions dominate both excitations and deexcitations, and thus

$$f_{se} = 1 - e^{-\frac{\Delta E}{kT}},$$

or $f_{se} \simeq \frac{\Delta E}{kT}$ for $\Delta E \ll kT$. The value of the line profile function at line center is

$$\phi(\nu_0) = \frac{1}{\sqrt{\pi \Delta \nu_D}}$$

assuming a Gaussian line shape (i.e. thermal broadening), where $\Delta \nu_D = \nu_0 \frac{b}{c}$ is the line width and $b = \sqrt{\frac{2kT}{mp}}$ is the Doppler parameter (Rybicki & Lightman 1979).

Table 1 compares the values of the parameters discussed above for Lyα versus the 21 cm line. The ratio of line center absorption cross sections is therefore

$$\frac{\sigma_\nu(\text{Ly} \alpha)}{\sigma_\nu(\text{21cm})} = 2.44 \times 10^6 T,$$

and since $T \geq 2.73$ K, Lyα is $10^7$ times more sensitive to H I absorption than the 21 cm line, if both absorption lines are optically thin. Note that when $N_{\text{H I}} > 2 \times 10^{11} T^{1/2}$, the Lyα line becomes optically thick, and the absorption equivalent width $EW = \int (1 - e^{-\tau_\nu})d\nu$ increases only as $\sqrt{\ln \tau}$.
Table 1. \textit{Lyα} versus 21 cm absorption line parameters

| Parameter | \textit{Lyα} | 21 cm |
|-----------|-------------|-------|
| $f_{12}$  | 0.416       | $5.75 \times 10^{-12}$ |
| $\phi(\nu_0)$ | $5.33 \times 10^{-10} T^{-1/2}$ | $9.27 \times 10^{-4} T^{-1/2}$ |
| $f_{se}$  | $\sim 1$   | 0.0682$T^{-1}$ |
| $n_2/n_1$ | $\ll 1$    | 3     |
| $\sigma_{\nu_0}$ | $5.88 \times 10^{-12} T^{-1/2}$ | $2.41 \times 10^{-19} T^{-3/2}$ |

Figure 1 presents a comparison of the absorption profiles of the 21 cm line vs. \textit{Lyα} for $10^{20} \geq N_{\text{HI}} \geq 10^{17}$ cm$^{-2}$. Note the large difference in absorption EW of the two lines. Jaffe (1990) measured in NGC 1275 21 cm absorption with $N_{\text{HI}} = 2 \times 10^{18}T$ and FWHM=477 km s$^{-1}$ (i.e. $b = 286$ km s$^{-1}$). The expected \textit{Lyα} absorption profile for $N_{\text{HI}}$ at various $T$ is displayed in Figure 2, indicating that for all $T$ one expects a very broad absorption trough with FWHM$\geq 2000$ km s$^{-1}$.

The \textit{Lyα} region in NGC 1275 was observed by Johnstone & Fabian (1995), and the observed spectrum is displayed in Figure 2 (velocity scale is relative to 5260 km s$^{-1}$). Clearly, the absorption predicted based on the 21 cm $N_{\text{HI}}$ is not present. The small trough at the center of \textit{Lyα} suggests absorption with EW$\sim 0.5$ Å, or 120 km s$^{-1}$. Johnstone & Fabian (1995) suggested that \textit{Lyα} is double peaked, rather than absorbed, in which case the absorption EW would be $\ll 0.5$ Å.

Clearly, \textit{Lyα} implies a much lower values for $N_{\text{HI}}$ than the 21 cm line. To obtain the $N_{\text{HI}}$ implied by \textit{Lyα} one needs to calculate EW($N_{\text{HI}}$), i.e. use the standard “curve of growth” analysis. Figure 3 displays the left hand side the \textit{Lyα} EW versus $N_{\text{HI}}$ for various values of the $b$ parameter (assuming a Gaussian velocity distribution). The EW increases linearly with $N_{\text{HI}}$ when the line is optically thin, saturating to EW$\propto \sqrt{\ln N_{\text{HI}}}$ when the line becomes optically thick, and recovering back to EW$\propto \sqrt{N_{\text{HI}}}$ when the Lorentzian wings dominate the absorption (‘damped’ absorption). The observed absorption EW of 120 km s$^{-1}$ translates to $10^{14} \geq N_{\text{HI}} \geq 4 \times 10^{17}$ cm$^{-2}$, where the upper limit is obtain if $b < 10$ km s$^{-1}$, and the lower limit is obtained if $b > 50$ km s$^{-1}$. The right hand side curves in Figure 3 represent the curves of growth for 21 cm absorption by H$\text{I}$ at $T = 10$ K. These curves are identical to those for \textit{Lyα} absorption, but shifted by a factor of $2.4 \times 10^7$ to the right hand side. The observed 21 cm absorption EW translates to $N_{\text{HI}} = 2 \times 10^{19}$ cm$^{-2}$ for a reasonable lower limit of $T = 10$ K. The largest column allowed by \textit{Lyα} is therefore $\sim 50$ times smaller than indicated by the 21 cm line.

3. How can the 21 cm and \textit{Lyα} columns be reconciled?

The apparent contradiction between the 21 cm and the \textit{Lyα} columns can be understood if the H$\text{I}$ column is highly non-uniform, and the spatial distributions of the background 21 cm and \textit{Lyα} emission are different. There is observational evidence that both these effects are present in NGC 1275. According to the
Figure 1. A comparison of the absorption profiles of the 21 cm line (right) vs. Lyα (left) for $10^{17} \geq N_{\text{H I}} \geq 10^{20}$ cm$^{-2}$. Note the large difference in velocity scales in the two panels.

Figure 2. The predicted vs. observed Lyα absorption profile. Left: The predicted absorption profile for different values of $T$ with $N_{\text{H I}} = 2 \times 10^{18} T$ and $b = 286$ km s$^{-1}$, as measured by Jaffe (1990). Right: The Lyα spectrum observed by Johnstone & Fabian (1995). Very little, if any, absorption is present in Lyα.
Figure 3. The Lyα and the 21 cm curves of growth for different velocity dispersions ($b$ parameters). The horizontal dashed lines indicate the observed absorption EWs, and the vertical dashed lines indicate the derived limits on $N_{HI}$. The largest column allowed by Lyα is $\sim 50$ times smaller than indicated by the 21 cm line.
21 cm continuum map presented by Jaffe (1990) most of the continuum originates within ±20″ of the center. Fabian, Nulsen, & Arnaud (1984) discovered with IUE that Lyα is also extended on ∼ 10″ scale, and the recent HUT observations by Van Dyke Dixon, Davidsen, & Ferguson (1996) indicate that Lyα emission of comparable surface brightness extends out to ∼ 60″ from the center. Evidence for spatially non-uniform absorption is seen on much smaller scales in the VLBA observations of Walker et al. (1994) and Vermeulen et al. (1994), who discovered a free-free absorbed counter jet to the north of the nucleus. The counter jet is most likely seen through a large column disk of relatively cold gas close to the center of NGC 1275 (Levinson et al. 1995), while the line of sight to the southern jet is clear. The large $N_{\text{HI}}$ indicated by the 21 cm line most likely resides on scales smaller than the ∼ 10−20 kpc scale of the Lyα emitting filaments. The low $N_{\text{HI}}$ indicated by Lyα provides a constraint for the ∼ 100−200 kpc scale absorber indicated by the X-ray observations.

4. **How can the X-ray and Lyα columns be reconciled?**

The various X-ray telescopes mentioned above indicate an excess absorbing column of $(1.5−4) \times 10^{21}$ cm$^{-2}$, and a covering factor close to unity. Such a column becomes optically thick at $E < 0.6−1$ keV. At this energy range O is the dominant absorber (e.g. Morrison & McCammon 1983). Thus, the X-ray spectra merely indicate the presence of an O column of $(1.3−3.4) \times 10^{18}$ cm$^{-2}$. The O X-ray absorption is done by the inner K shell electrons, thus the ionization state of the O can be anywhere from O I to O VII.

The X-ray and Lyα constraints imply that whatever is producing the absorption on the ∼ 100 kpc scale in the Perseus cooling flow cluster must have $3 < N_{\text{O}}/N_{\text{HI}} < 3 \times 10^4$, i.e. it is drastically different from a neutral, solar abundance absorber, where $N_{\text{O}}/N_{\text{HI}} = 8.5 \times 10^{-4}$.

If the absorber has roughly solar abundance then H must be highly ionized with $2.5 \times 10^{-8} < N_{\text{H}}/N_{\text{HI}} < 2.5 \times 10^{-4}$. Can H be so highly ionized? The available ionizing flux is far too low for significant photoionization. Collisional ionization requires $5 \times 10^6 > T > 5 \times 10^4$ K, where the upper limit prevents O from being too highly ionized. However, this temperature range is excluded based on the absence of significant line emission (e.g. Voit & Donahue 1995). It thus appears that the required ionization state of H is ruled out. The above constraints on $T$ assume equilibrium ionization states. It remains to be studied whether plausible deviations from ionization equilibrium can significantly affect the ionization state of H.

Another possibility is that the absorber has practically no H. This would be the case if the absorption originates in O which resides in dust grains embedded in hot gas. However, the dust sputtering time scales appear too short to explain the absorption in the inner parts of clusters (Dwek et al. 1990; Voit & Donahue 1995).

Could most of the H be in molecular form? CO emission was detected in the Perseus CF (e.g. Braine et al. 1995) indicating that some of the H is indeed in molecular form. However, the H I/H$_2$ fraction needs to be $< 2.5 \times 10^{-4}$, while theoretical calculations (Ferland et al. 1994) indicate that most of H (> 80%) would be in atomic form, even in extremely cold clouds embedded in CFs.
Figure 4. The expected Ly$\alpha$ profile in NGC 1275 at a high spectral resolution ($\sim 10$ km s$^{-1}$). Left: Emission + absorption profiles. Right: Blowout of the absorption profile. Such a spectrum would allow a rather accurate determination of $N_{\text{H I}}$. If the H I gas has a very low velocity dispersion the absorption will go black, and if the velocity dispersion is high the absorption profile will remain shallow.

It therefore appears that there is no satisfactory model which explains the X-ray absorption together with the new tight limits on $N_{\text{H I}}$ obtained from Ly$\alpha$.

5. Future perspectives

Given the difficulty in finding a plausible explanation for the X-ray absorption, it is crucial to verify that this absorption is indeed real. This can be achieved by the detection of an O bound-free K edge at the CF cluster redshift (see Sarazin, these proceedings). The edge energy will also indicate the ionization state of the absorber. This can be achieved with next generation high resolution X-ray telescopes.

On a shorter time scale, significantly better constraints on $N_{\text{H I}}$ in NGC 1275 can be obtained with HST. Currently, the actual value of $N_{\text{H I}}$ in NGC 1275 is uncertain by nearly 4 orders of magnitude, and a much more accurate determination can be achieved through a higher resolution UV spectrum, as demonstrated in Figure 4.

The method described here can be extended to many more CF clusters. All CF clusters have a large cD galaxy at their center, and these galaxies tend to have a power-law continuum source at their center with significant UV emission which can be used for the detection of Ly$\alpha$ absorption. In addition, significant Ly$\alpha$ emission most likely originates from the emission line filaments present in
all CF clusters. For example, Hu (1992) observed 10 CF cluster with the IUE, detecting significant Lyα emission in 7 clusters, thus demonstrating that the method described here can be applied to most CF clusters.

The disadvantage of using the central cD galaxy is that if absorption is detected it may be produced by gas local to the cD or the emission line filaments, rather than the large scale absorber. The lack of significant absorption can, however, be used to place stringent limits on the nature of the X-ray absorber.

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