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CORONAL LINE EMISSION IN CLUSTER COOLING FLOWS

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ABSTRACT

We report one marginal detection (PKS 0745−191) and four nondetections (A2199, 2A0335+096, A2597, and A1795) of the coronal emission line [Fe x] 6374 Å radiated by $\sim 10^6$ K gas in the central regions of massive cooling flow clusters (mass cooling rates of $\dot{M} \geq 100\ M_\odot\ \mathrm{yr}^{-1}$). Except for the nondetection of [Fe x] in A1795, these observations are consistent with and more sensitive than previous upper limits for these and similar clusters of galaxies. We discuss in detail the specific difficulties in detecting this emission line against the starlight and the $\sim 10^4$ K emission-line region of the central cD.

The [Fe x] emission directly probes the radiative behavior of cooling gas in the central 10 kpc of the cluster, which X-ray telescopes cannot yet spatially resolve. The [Fe x] detection in PKS 0745−191 cannot be explained by any plausible photoionization or gas heating model for cluster gas, except for the standard cooling gas picture.

The [Fe x] luminosity measures (1) the cooling rate of gas in the centers of these clusters, and (2) the amount of photoionizing UV radition that is generated by cooling gas. Such UV radiation can photoionize and heat the luminous, cool ($\sim 10^4$ K) filaments. The level of the detection and upper limits reported here suggest that a fraction ($\lesssim 30\%$) of the rate of mass cooling observed by X-ray telescopes over extents of 100 kpc occurs in the central 10 kpc, and thus within the central cD itself. In addition, the [Fe x] strength is consistent with models for photoionizing the 10^4 K nebular filaments by cooling hot gas (e.g., self-ionized cooling filaments, turbulent mixing layers, or stripped interstellar medium photoionized by cooling gas), although upper limits a few times more sensitive than the limits presented here would challenge the simplest of these models.

Subject headings: cooling flows — galaxies: clustering

1. INTRODUCTION

Clusters of galaxies are among the most luminous X-ray emitters at photon energies of 0.5–2.0 keV. Their radiation is generated by thermal bremsstrahlung in the hot, diffuse intracluster medium (ICM) at 10^7–10^8 K. In some cases, this hot plasma, bound by the gravitational potential of the cluster, may be dense enough to cool and settle in the central region of the cluster in a "cooling flow." The hot gas in many X-ray emitting clusters is cooling quickly, at estimated rates of 10–100 $M_\odot\ \mathrm{yr}^{-1}$ (Edge, Stewart, & Fabian 1992.) X-ray spectroscopy provides the most convincing evidence that the gas is indeed cooling from 10^8 K to 5×10^6 K (see Mushotzky 1992; Canizares, Markert, & Donahue 1988; Mushotzky & Szymkowiak 1988). The controversy associated with cooling flows is that little evidence exists, other than X-ray spectra and images, for the large mass deposition rates which would accompany such copious cooling. Indeed, some authors have suggested that not cooling but heating is occurring in clusters (e.g., Sparks, Macchetto, & Golombeck 1989; de Jong et al. 1990; Bregman 1992; Sparks 1992); thus the very existence of cooling flows is still somewhat controversial (but see rebuttals by Canizares et al. 1993, and Fabian, Nulsen, & Canizares 1991).

This experiment was designed to measure the mass cooling rate independently from the X-ray observations. The rate of mass cooling through intermediate temperatures ($10^{6.5}$ to $10^{5.5}$ K) can be measured via emission lines such as [Fe x] 6374 Å and [Fe XIV] 5303 Å, as outlined by Cowie (1981). This is the same method used to estimate cooling rates from X-ray emission lines (Canizares et al. 1988). It is the most compelling way to measure cooling rates because it is nearly model independent, and the line luminosity relies only upon the atomic physics and ionization-recombination processes in a cooling plasma. Sarazin & Graney (1991) calculated models for optical coronal emission from cooling flows. The spatial dependence of mass deposition in the cooling flow affects the surface brightness of the line emission, but not its total luminosity. The plasma traced by these faint optical emission lines cools efficiently, and is even more strongly thermally unstable than gas at 10^7 K, which is traced by X-ray emission lines such as Fe XVII at 826 eV. Detection of gas at a million degrees indicates a temperature contrast within the cluster of greater than a factor of 100. Even factors of 10 in temperature are difficult to reproduce in the heating models proposed to resolve the cooling flow controversy (Bregman & David 1989; Nulsen et al. 1982; Loewenstein, Zweibel, & Begelman 1991; Canizares et al. 1993). Thus, the detection of [Fe x] 6374 Å would strongly support the existence of cooling flows.

Furthermore, the optical emission-line nebulae seen in the central ~ 10 kpc of many cooling flow clusters provide evidence of prodigious energy sources in cluster cooling flows. The extremely high Balmer-line and forbidden-line luminosities of these nebulae require a substantial input of energy. The unusual spectra of these nebulae (e.g., high [N II]/Hα ratios; [O II] $\gg$ [O III]) seem to suggest that EUV–dominated photoionization may be occurring (Donahue & Voit 1991). Photoionization by a central nonthermal source or by hot stars cannot reproduce the spectral line ratios (Johnstone, Fabian, & Nulsen 1987; Johnstone & Fabian 1988; Heckman et al. 1989). The remaining energy source is the gravitational energy of the cluster, which provides the energy reservoir for the intracluster medium and for the turbulent energy of galaxy wakes or shocks arising from the kinetic energy of the member galaxies. If the gravitational energy of the cluster is powering the filaments, the luminosities of the filaments require that the stored gravitational energy of 10–100 solar masses per year be converted efficiently to emission-line radiation in the UV and optical bands. For this reason, any model for powering the optical nebulae which taps the energy of the ICM must be very efficient in order to explain the highest luminosity nebulae. This class of models includes EUV photoionization models (Voit & Donahue 1990), photoionization by turbulent mixing layers (Begelman & Fabian 1990), and photoionization by gas heated in fast shocks (Binette, Dopita, & Tuohy 1985), presumably stemming from galaxy ISM–cluster ICM interactions or from radio source plasma–cluster ICM interactions. We can directly test the simplest of these models, in which radiative cooling of the ICM provides the energizing EUV radiation, by measuring the [Fe x] emission near the filaments, and comparing this measurement to the predicted [Fe x] emission in the models.

Several attempts have been made to detect the presence of optical coronal emission lines from cooling flows. Long-slit spectra of several cooling flows by Hu, Cowie, & Wang (1985) showed no emission from [Fe xiv] 5303 Å but gave nonrestrictive upper limits. Heckman et al. (1989) attempted detection of [Fe x] 6374 Å in spectra of cooling flows, and derived upper limits to the [Fe x]/Hα ratio. These scaled total [Fe x] luminosity limits are tantalizingly close to luminosities predicted by the X-ray cooling rates. However, scaling [Fe x] by the Hα luminosity, and thus assuming that the [Fe x] and the Hα emission are spatially correlated, is not necessarily correct since the [Fe x] and Hα emission are not generated from the same gas. Recently, Anton, Wagner, & Appenzeller (1991; AWA hereafter) have reported a detection of [Fe x] from the central region of the cooling-flow cluster A1795 that is somewhat higher than would be predicted by the cooling rates derived for this source. We do not confirm this detection, as we discuss below. As part of a larger program to study the emission-line nebulosities associated with NGC 1275, Shields & Filippenko (1992) searched for [Fe x] emission associated with the off-nuclear region of NGC 1275 (away from the well-known active galactic nucleus [AGN]). They place upper limits to the off-nuclear surface brightness of [Fe x] that are a factor of 5–10 below previous limits for cooling-flow clusters of galaxies.

Detecting [Fe x] is very difficult because one is attempting to discern a very faint emission line against a background of starlight continuum emission and, in some cases, the wings of a strong, broad [O i] 6363 Å emission line. Theoretical models in which mass decouples from the cooling flow at $r \gg 10$ kpc predict a very low surface brightness of [Fe x]. Obviously, if the cooling flow fades to nothing in the center, this detection attempt is a hopeless enterprise indeed. The detectability estimates by Sarazin & Graney (1991) are optimistic, because they do not take into account the underlying galaxy light. However, if the optical filaments are powered by photoionization from cooling gas or gas heated by fast shocks, coronal gas must exist near these filaments, and thus observations of [Fe x] will prove valuable for testing filament energization models and cooling flow models where at least some of the cooling gas cools through 10^6 K within 10 kpc of the cluster center.

2. OBSERVATIONS

In order to detect or to place significant limits on cooling rates in the central regions of cooling flows and to test models for powering the optical filaments, we have observed the central galaxies of five cooling flow clusters: PKS 0745−191, A2199, A2957, 2A 0335+096, and A1795. We acquired spectra centered on the nuclei of the central galaxies of these clusters of galaxies at position angles selected to lie along the high surface-brightness, Hα emission-line filaments. We also obtained template spectra of two giant elliptical galaxies, MKW 1 and MKW 2, which do not contain emission-line gas.

Medium-resolution spectra were acquired with the red channel of the Double Spectrograph on the 5 m Palomar telescope in 1991 August, 1991 December, and 1992 December, and with Modular Spectrograph on the Las Campanas du Pont 2.5 m telescope in 1992 December. The Double Spectrograph has two TI 800 × 800 pixel back-illuminated CCDs. One 15 μm pixel corresponds to 0″.58 at the entrance slit in the spatial direction and ∼0.816 Å in the spectral dimension. The Modular Spectrograph was fitted with a CRAF 1024 × 1024 pixel CCD and the 85 mm camera. A single pixel corresponds to ∼1.18 Å in the spectral dimension and 0″.5 pixel^{-1} in the spatial dimension. For all observations, we used 1200 line per mm gratings blazed at 7500 Å and entrance apertures of 2″. The spectrograph slits for both instruments are over 2′ long, so we were able to expose ample sky as well as nebulae and galaxies.

We obtained multiple observations of each object, for totals of 4 and 7 hr for A2199 and A2957, respectively, on the night of 1991 August 13–15. 2A 0335+096 was observed for 4.5 hr in 1992 December. A1795 was observed for 2 hr total at the end of the night in 1992 December. The seeing during the 1991 August nights was 1″.5 and was only 2″.0–2″.5 during the 1992 December nights. Both sets of observations were nearly photometric. Some of the comparison spectra for galaxy templates were obtained during two bright nights of poor seeing (up to 3″.0) in 1991 December at Palomar. Three spectra of PKS 0745−191 were acquired on 1992 April 12 during photometric conditions and good seeing (<1″.5). Additional spectra were accumulated during similar conditions 1992 December 16–18. We obtained a low-resolution spectra containing Hβ and [O iii] of PKS 0745−191 in 1991 February. We list instrument information in Table 1, and exposure times, position angles, and extraction information in Table 2.

The frames were reduced in a standard manner in IRAF using co-added dome flats. Illumination corrections were found to be unnecessary for our purposes since the extracted spectra were all well-centered. Two-dimensional wavelength solutions for the arcs were found using low-order spline functions, and the frames were rebinned. We report the rms deviations per pixel for the wavelength fits in Table 1. The sky background was fitted in specified sections along each line perpendicular to the spectrum and subtracted.

Flux calibration was accomplished for Palomar data by observations of standard stars BD +26°2606, BD +33°2642, Feige 110, and BD +25°3941. We tested for variation of sensitivity along the slit by observing the star BD +33°2642 at

TABLE 1

Observatory Information and Instrumental Setups

Cluster cD	Observatory and Aperture	Dates	Resolution (Å)	rms ID Fit (Å)	Coverage (Å)
A2199	P200	1991 Aug 14–15	2.0	0.2	6502–7135
A2597	P200	1991 Aug 14–15	2.0	0.8	6502–7153
MKW 1	P200	1991 Dec 20	2.0	0.7	6343–6994
MKW 2	P200	1991 Dec 21	2.0	0.7	6343–6994
MKW 2	P200	1992 Dec 31	2.0	0.7	6540–7190
2A 0335+096	P200	1992 Dec 31	2.0	0.7	6540–7190
2A 0335+096	LC100	1992 Dec 16, 18	3.0	0.12	6465–7621, 6528–7730
PKS 0745−191	LC100	1992 Dec 16–18	3.0	0.12	6465–7621, 6528–7730

various positions along the slit. We found variations of up to 15% at the edges of the red chip of the Double Spectrograph, but in the area where we extracted spectra, the variations were negligible (less than 2%). The Modular Spectrograph was even better illuminated with only 0.2% variations in flattened twilight observations along the slit. The Las Campanas April observations were flux-calibrated with the southern standards L745-46A and LTT 6248, December observations with L745-46A, LTT 377, LTT 1020, and LTT 2415.

We combined the frames for individual sources, weighted by the signal-to-noise ratios of the individual observations. These ratios did not vary much from observation to observation so that a single observation does not dominate the combined spectra of a given cluster galaxy. The main source of noise for detection of [Fe x] is the galaxy continuum. The sky, although it is an important source of noise for the total (continuum + emission line) galaxy spectra, does not contribute as much noise as does the continuum when determining uncertainty in the net emission-line flux limits. The readout noise for all CCDs used is about 10 electrons per pixel, negligible in these long observations.

The cD galaxies MKW 1 and MKW 2 do not have emission lines and are near the redshift of the cooling flow sources we observed, so they are reasonable templates for comparison with the emission-line sources. Although the data are too noisy to directly subtract from the emission-line data, we found that the continuum spectra of these galaxies near the rest wavelength of [Fe x] 6374 Å is largely featureless. However, there is a broad absorption feature in the galactic continuum just blueward of the [O I] 6363 Å line, near 6360 Å. This feature also appears in the difference spectra between the scaled and shifted [O I] 6300 Å profile and the [O I] 6363 Å of the emission-line nebulae. Since the absorption is blueward of 6363 Å, it poses no problem for the identification of [Fe x], but it does reduce the observed [O I] 6363 Å/6300 Å ratio below the theoretical value of $\frac{1}{3}$.

TABLE 2

Exposure and Extraction Data

Cluster Name	Redshift	Extraction Width	Position Angle East of North	Total Exposure Time (s)
PKS 0745−191	0.1028	5″.0	30, −30, 25, 90	26700
A2199	0.0312	5.8	105, 90	8100
A2597	0.0821	5.8	30	12600
A1795	0.0630	4.1	345	7200
2A 0335+096	0.0350	5.8	140, 135, 130	16200

In addition, direct [O I] profile subtraction can be affected by the emission line [S III] 6312 Å. Although this line is expected to be weak, it may blend with the [O I] 6300 Å profile. This creates a problem in measuring a standard profile, since the wavelength offset from the 6300 Å oxygen line is similar to the offset of [Fe x] from the 6363 Å oxygen line. But for the physical conditions observed in the nebulae, the [S III] 6312 Å feature is not expected to be important here, as we discuss in the next section.

3. DETECTIONS AND UPPER LIMITS

We estimate the sensitivity of our observations in the following way. We fit and subtract a smoothed continuum from the spectra. We then determine the rms deviations from zero in the continuum regions of the spectra. We fit Gaussians to the strong emission lines in order to estimate the average FWHM of the lines. The 3 σ upper limits are then estimated by $F(3\,\sigma) = 3\,\sigma_{\rm rms}\,N_{\rm bin}^{1/2} + 3\,\sigma_{\rm rms}[{\rm FWHM(Å)}/d]^{1/2}$, where d is the dispersion in Å per pixel. This method accounts for all systematic uncertainties, including those arising from undetected continuum spectral structure. Additional uncertainties may arise from extreme velocity structure in the optical emission-line gas and line blending between the [O I] 6363 Å and [Fe x] 6374 Å lines. For the observations which included [O I] 6300 Å in the wavelength coverage, we compared the scaled line profile of [O I] 6300 Å to that of [O I] 6363 Å. The [O I] 6300 Å line profile may be contaminated by the presence of [S III] 6312 Å, but photoionization models that successfully reproduce the other line ratios (Donahue & Voit 1991) predict this line to have 0.9% the Hα flux, compared to typical [O I] 6300 Å fluxes ~25% the Hα flux (Heckman et al. 1989; this work). Therefore, for the ionization parameters (the ratio between ionizing photon number density and hydrogen number density) and electron densities derived from line ratios in cooling flows, we do not expect significant contributions from [S III] 6312 Å. When we scale from [O I] 6300 Å to [O I] 6363 Å, the predicted [S III] 6312 Å flux is reduced to a factor of several below the noise in our spectrum. Although it is not significant for the purposes of detecting [Fe x] at the flux sensitivities in this experiment, this systematic contamination should be considered in future, improved studies of this kind.

In Table 3, we report our 3 σ upper limits and detection with 1 σ error bars as derived from estimating the uncertainty in continuum emission. We also calculate the bounds on the [Fe x]/Hα ratio, which is relevant to models which rely on hot gas to provide photons for energizing the filament gas. We derive limits on the mass cooling rate for the region of the cluster sampled by the spectroscopic slit. For comparison,

TABLE 3

FLUXES AND MASS COOLING RATES

Cluster	rms[a] (10^{-16} ergs s^{-1} cm^{-2} $Å^{-1}$)	Flux[b] (10^{-17} ergs s^{-1} cm^{-2})	[Fe X]/Hα	$\dot{M}_{Fe\,X}$ ($M_\odot$ yr^{-1})	$\dot{M}_x$ ($M_\odot$ yr^{-1})
PKS 0745−191	0.70	6.9	0.060	160 ± 50	500
2A 0335+096	1.2	<4.3	<0.0075	<11	100–180
A1795	1.7	<2.0	<0.011	<170	500
A2199	1.0	<1.2	<0.018	<24	100–200
A2597	1.3	<1.6	<0.0045	<23	160

[a] rms fluctuation size in the continuum after a smooth continuum was subtracted.
[b] Upper limits are 3 σ. Listed uncertainties are 1 σ.

Table 3 contains the cooling rate summed over the entire cluster, derived from X-ray observations (Edge et al. 1992).

From a flux limit or detection in an object at redshift z, we can convert directly to a mass cooling rate or limit by the following expression:

$$L([\mathrm{Fe\ X}]6374) = 2.10 \times 10^{37}\ \mathrm{ergs\ s^{-1}}\ \frac{\dot{M}}{100\ M_\odot\ \mathrm{yr}^{-1}}\,, \quad (1)$$

or in terms of observable quantities:

$$\frac{\dot{M}}{100\ M_\odot\ \mathrm{yr}^{-1}} = \begin{cases} 81.6 f_{17} h_{50}^{-2}[(1+z)-(1+z)^{0.5}]^2\,, & (q_0 = 0.5)\,, \\ 20.4 f_{17} h_{50}^{-2}\{10z - 90[(1+0.2z)^{0.5} - 1]\}^2\,, & (q_0 = 0.1)\,, \end{cases} \quad (2)$$

where f_{16} is the [Fe X] flux divided by 10^{-17} ergs s^{-1} cm^{-2}, and h_{50} is the Hubble constant $H_0/50$ km s^{-1} Mpc^{-1}. We note that the wavelength for [Fe X] is 6374.51.

To derive this relationship, we used the spectrum emitted by gas with solar abundances cooling from a temperature of 10^7 K (Voit, Donahue, & Slavin, 1993; VDS hereafter). VDS reports line ratios for emission lines expected from cool gas irradiated by cooling, hot gas at infrared through the X-ray wavelengths. VDS includes the effects of nonequilibrium cooling, which increases the amount of [Fe X] emission expected per unit mass by ~40% over the equilibrium cooling calculations of Hu et al. (1985).

VDS assumes solar abundances for their calculations, but typical iron abundances in clusters are ~0.3 solar. However, since iron is the main coolant over the temperatures 10^6–10^7 K, our assumption of solar abundances does not matter significantly. As long as iron is the primary coolant at 10^6–10^7 K, the luminosity of [Fe X] will not vary strongly with metallicity. Variations in relative abundances (e.g., oxygen to iron) will, however, change the flux ratios of those lines. For example, the oxygen to iron abundance ratio may be a factor of 3 greater than the solar ratio in clusters (Canizares et al. 1982, 1988) which could decrease the ratio of iron to oxygen *coronal* emission.

3.1. *PKS 0745−191*

We detect [Fe X] at the 3 σ level in PKS 0745−191. In a sum of 10 exposures totaling 23,000 s at two different position angles centered on the galaxy nucleus, we find a flux level of 6.9×10^{-17} ergs s^{-1} cm^{-2} at the position of [Fe X]. This corresponds to a mass cooling rate of 160 ± 50 $M_\odot$ yr^{-1} in the central portion ($13 \times 5h_{50}^{-1}$ kpc) of the galaxy. When we scale the [O I] 6300 Å profile to [O I] 6363 Å, we do not see any velocity structure that might reproduce the apparent [Fe X] feature (Fig. 1). We subtract the scaled profile from the data and plot the residuals. Individual spectra, summed for each night with slightly different spatial and spectral locations on the CCD, show some evidence for excess emission at the rest wavelength of [Fe X]. We calculated a redshift appropriate for each of the strong emission lines in the spectrum, and the derived redshifts are consistent with each other to within 0.7 Å. Based upon the arc lamp wavelength solution, the position of the [Fe X] feature is well within a standard rms deviation of the expected [Fe X] position. The fact that the feature appears in more than one spectrum, including one taken 7 months earlier with the grating at a different angle, at the expected wavelength, lends credibility to the formally weak detection.

3.2. *A2597*

In A2597, we find a suggestive wing on the [O I] 6363 Å line near the wavelength of [Fe X]. However, when we scale [O I] 6300 Å to [O I] 6363 Å, we do not detect [Fe X] clearly in this object (Fig. 2). Since [O I] is very strong and the optical emis-

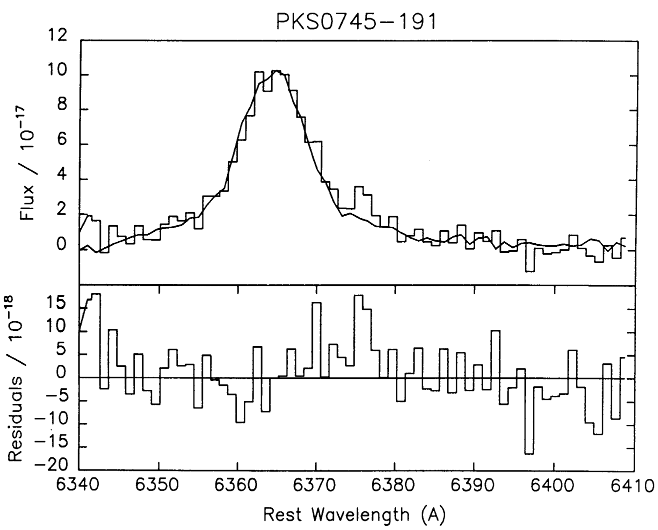

FIG. 1.—Modular Spectrograph spectrum for PKS 0745−191. A smooth continuum has been fitted and subtracted from the emission-line spectra. The upper figure shows the [O I] 6300 Å line template rescaled and overplotted on the [O I] 6363 Å feature, and the lower figure shows the residual spectrum. The reported [Fe X] 6375 Å feature can be seen and is the only statistically significant residual feature. The widest spectrum contiguous to the [O I] 6363 Å line is plotted. The red limit is bounded by the wings of the strong [O I] 6300 Å line and the blue boundary is at the wavelength of a strong atmospheric absorption feature.

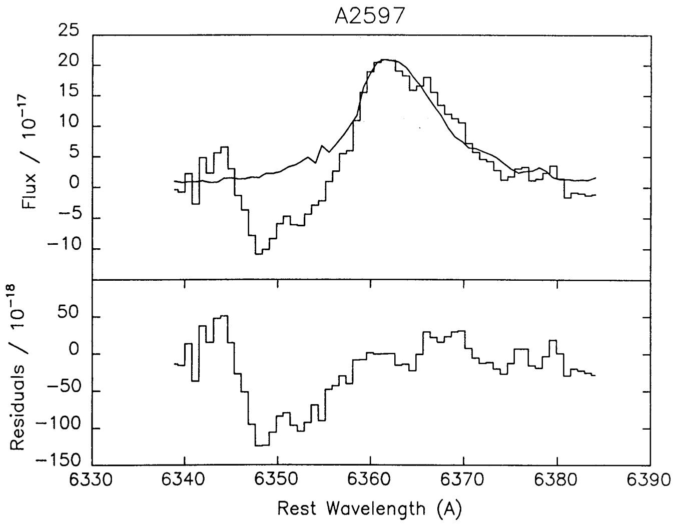

FIG. 2.—Double Spectrograph spectra for A2597. This figure shows the [O I] 6300 Å line template rescaled and plotted over the [O I] 6363 Å feature, with the residuals plotted below. A smooth continuum was subtracted from the emission-line spectra. We detected no [Fe X] at the nominal [Fe X] rest wavelength.

sion lines are significantly velocity broadened (550 km s^{-1} FWHM), [O I] is blended with [Fe X], and the rms noise in the spectrum is increased near the wavelength of [Fe X]. Our reported upper limit reflects that increase.

3.3. *A1795*

For A1795, [O I] 6363 Å is clearly partially absorbed by the underlying Fe II absorption feature, as illustrated by the overplot of the [O I] 6300 Å line profile over the continuum-subtracted [O I] 6363 Å feature (Fig. 3). In a comparison of this observation to the detection reported by AWA, we see that the [Fe X] feature reported by AWA would have been clearly detected in one spectrum with a similar significance to theirs. However, we do not detect [Fe X] in this cluster, even though we were careful to observed and analyze the same emission-line region as AWA. We do see excess flux at the position of [Fe X] but the formal significance of this feature is less than 3 σ. We discuss explanations for our discrepant observations in the discussion section.

3.4. *2A 0335+096*

We found no indication of [Fe X] 6374 Å with a 3 σ confidence level of 4.3×10^{-17} ergs s^{-1} cm^{-2} in the X-ray cluster 2A 0335+096, corresponding to a cooling rate of less than 11 $M_\odot$ yr^{-1} h_{50}^{-2} in the region which is $5.6 \times 1.9 h_{50}^{-1}$ kpc around the central nucleus. We note that this [Fe X] upper limit, when divided by the large Hα flux in the same observation, comes the closest to challenging the requirements of the Donahue-Voit photoionization model. We display a sample spectrum in Figure 4.

3.5. *A2199*

In A2199, [O I] 6363 Å appears to be fairly weak and partially absorbed by the underlying continuum feature. [O I] 6300 Å was not included in the wavelength coverage. There are two spectral emission features, neither of which exceeds our derived 3 σ upper limits, one at rest wavelength of 6371 Å and the other at 6378 Å (Fig. 5). The wavelengths of neither of these features correspond to that of the expected [Fe X] emission, unless the hot gas is moving at velocities ± 150 km s^{-1} with respect to the optically emitting gas. Therefore these spikes are most likely noise.

4. DISCUSSION

In this section, we discuss the two clusters in which [Fe X] detections have been reported by us or by AWA. We then discuss the theoretical models for the source of [Fe X] emission. We then report the constraints placed on models of cooling gas in clusters of galaxies and on models for powering the optical emission-line nebulae found in clusters thought to contain cooling flows.

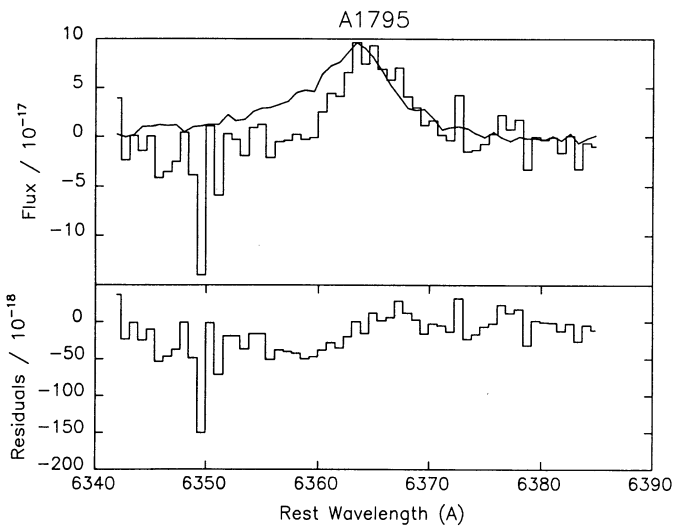

FIG. 3.—Double Spectrograph spectra for A1795. We plot the scaled [O I] 6300 Å line profiles over the [O I] 6363 Å line. There is excess flux at the nominal rest wavelength of [Fe X], as can also be seen in the plot of residuals, but the significance of this feature is much less than 3 σ.

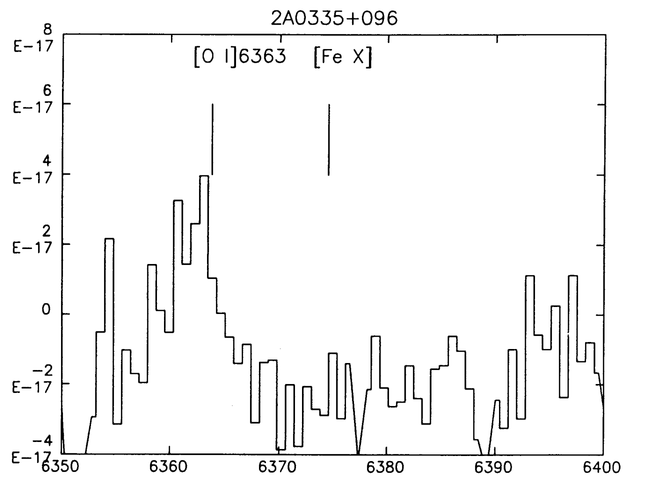

FIG. 4.—Double Spectrograph spectra for 2A 0335+096. A similar spectrum was obtained at Las Campanas. The wavelength coverage did not include [O I] 6300 Å, but if the [Fe X]-emitting gas has the same velocity dispersion as the cooler 10^4 K gas, the line profiles of [Fe X] and [O I] 6363 Å would be too narrow to overlap. Therefore this cluster is a good candidate for further observations.

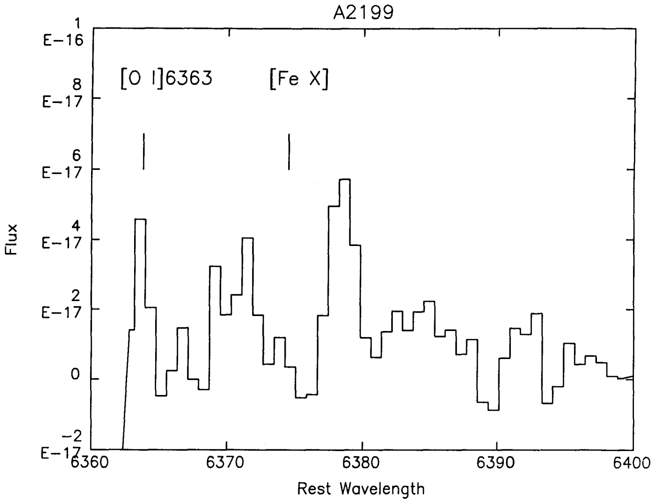

FIG. 5.—Double Spectrograph spectra of A2199. No [Fe x] was detected in this cluster. [O I] 6300 Å was not included in the bandpass, and [O I] 6363 Å is very weak. It is likely that the underlying absorption feature dominates over the emission-line radiation in this object and bandpass. The emission "features" in this spectra are well below the 3 σ detection limit allowed by continuum noise.

4.1. *A1795: Clumpy Hot Gas?*

AWA reported a 7 σ detection of [Fe x] in the nuclear region of A1795 at a level of 2.2% of Hα. We observed the same region of A1795 and derive a 3 σ upper limit that is 1.1% the Hα flux. There are three possible interpretations of these conflicting reports. Either AWA overestimated the significance of their feature, or we have underestimated the errors in our own spectrum, or the 10^6 K gas which produces [Fe x] is very clumpy, and we were not observing exactly the same regions of the central galaxy in A1795.

We can rule out the possibility of underestimating our own uncertainties if we compare the size of the flux feature expected in our spectrum with what we observe. The AWA flux feature would have been straightforward to detect in our observations. We cannot address how the uncertainties were handled by AWA, but the spectra that they publish do seem to be statistically significant.

The million-degree gas in a cooling flow could be lumpy. Indeed, the hotter, X-ray emitting gas in the central portion of a cooling flow is not smoothly distributed. Evidence for this is seen in the *ROSAT* HRI observations of 2A 0335+096 and A2029 which show filamentary structures in the X-ray surface brightness maps of these clusters (Sarazin, O'Connell, & McNamara 1992a, b). Variations in X-ray surface brightness in the *ROSAT* energy bands are likely caused by variations in gas density, since temperature variations must be quite large to induce comparable luminosity perturbations in the soft X-ray bandpass of *ROSAT*. The linewidths of the optical emission lines seem to indicate that there may be turbulence in the hot gas. Models of cooling flows which successfully reproduce the X-ray spectral and imaging observations require that any "flow" must be heterogeneous (cf. Fabian, Nulsen, & Canizares 1984). Finally, in models for the emisson-line nebulae in cooling flows, the irradiating gas need not be exactly cospatial with the nebular gas, since the hot gas is optically thin to EUV photons. For the two above reasons, it may not be surprising to find that the coronal emission from such gas is lumpy. We suggest that the [Fe x] emission in A1795 is highly clumped which accounts for some if not all of the discrepancy between our observations and those of AWA.

4.2. *PKS 0745−191*

PKS 0745−191 has one of the strongest known cooling flows, with an estimated mass cooling rate of $\sim 500\ M_\odot\ \mathrm{yr}^{-1}$ (Fabian et al. 1985; Arnaud et al. 1987). It has an Hα luminosity comparable to that of the Perseus cluster (see Caulet et al. 1992 for new Perseus Hα data). Excess blue light in the center 15 kpc, if generated completely by massive stars, implies a star formation rate of 10 $M_\odot\ \mathrm{yr}^{-1}$, assuming a Galactic IMF (Romanishin 1987). This galaxy has been studied extensively in the radio by Baum & O'Dea (1991). Its radio luminosity ($L_R \sim 8 \times 10^{42}$ ergs s^{-1}) is anomalously high for the diffuse radio morphology of the source. Sources of similar radio power and at similar redshifts have classical double morphologies and are located in sparse environments (e.g., Lilly & Prestage 1987; Prestage & Peacock 1988).

The detection reported in this paper suggests that about 30% ± 10% of $\dot{M}_x$ observed at larger radii is accreting to the central few kpc of PKS 0745−191 and cooling further there. The percentage required for cooling condensates to supply all of the radiative energy to the filaments is nearly 20%, well within the uncertainties of the observed flux. The detected coronal emission is consistent with that predicted by inhomogeneous cooling flow models in which most of the cooling gas decouples from the flow at radii larger than a few kpc. The [Fe x] mass cooling rate is also consistent with the star formation rate reported by Romanishin (1987), but the similarity of the rates is probably coincidental, since the star formation rates are based on the highly uncertain assumption that star formation in cooling flows is similar to the star formation in our own Galaxy, (i.e., a Salpeter IMF was assumed). Nevertheless, the [Fe x] luminosity is within the range expected for the general cooling flow model of this cluster.

4.3. *Tapping the ICM: Access to the Cluster Gravitational Energy*

The most promising models for the [Fe x] emission also incorporate explanations for the production of the luminous nebular emission seen in the centers of many cooling flow clusters. As we explained in the Introduction, the luminosity of the filaments in Balmer lines and low-ionization forbidden lines requires an input of energy equivalent to the gravitational energy of 10–100 solar masses in the cluster potential per year. Models that involve the extraction of gravitational energy from the hot gas include photoionization by cooling condensations (Voit & Donahue 1990), photoionization by turbulent mixed layers (Begelman & Fabian 1990), and photoionization by gas shocked to high temperatures by fast shocks (Binette et al. 1985). In all of these models, hot gas cools and radiates an ionizing spectrum in which EUV photons dominate. Models that incorporate the cooling of the gas self-consistently with the irradiation of gas that is already cold can predict the minimum amount of [Fe x] required for the models to be viable. (The trace quantity of nebular gas present probably did not condense from the hot gas, see Donahue & Voit 1993.) We discuss [Fe x] in the context of the cooling condensations in § 4.4. But before we do this, we will examine whether active nuclei or supernovae can generate the observed [Fe x]. We will show that neither AGNs nor supernovae can generate the [Fe x] detected in PKS 0745−191. If the detection of [Fe x] in PKS 0745−191 is real, it provides powerful evidence for the

TABLE 4

IMPLIED COVERING FRACTION OF NEBULAR GAS TO HOT GAS IN THE FILAMENT REGIONS

Name	Covering Fraction
PKS 0745−191	0.65 ± 0.35
2A 0335+035	>0.43
A1795	>0.30
A2199	>0.18
A2597	>0.72

presence of a substantial amount of cooling gas in the center of this cluster.

4.3.1. *Photoionization by a Central Source*

Because many cluster cooling flows also have minor AGNs, one might surmise that a nuclei source of [Fe x] could be due to photoionization by a central source (e.g., Korista and Ferland 1989). We believe we can rule out photoionization as a source for [Fe x] in these objects because the photoionization parameter required to produce [Fe x] is higher than observations suggest. If iron atoms were stripped of nine electrons by energetic photons from a central source, one would expect [O III] to be strong in these sources, and it is not. As we have measured in lower resolution observations of PKS 0745−191, [O III] 5007 Å/Hβ ~ 1.0, typical of other cluster nebulae. This ratio is an order of magnitude smaller than would be expected if nuclear photoionization were causing the production of [Fe x]. High [O III] luminosities are measured in radio galaxies, where the detected [Fe x] is likely caused by photoionization by a central source (e.g., Owen, O'Dea, & Keel 1990). Shields & Filippenko (1992) similarly rule out central photoionization as a source for any [Fe x] emission from NGC 1275. However, as Hβ may be emitted by gas located farther from the nucleus than the gas that is presumably photoionized by a nuclear source and producing [O III], the appropriate ratio to consider may be [O III]/[Fe x]. In photoionization models where a central photon source is responsible for producing both O III and Fe x, and the O/Fe ratio is cosmic, the [O III]/[Fe x] ratio is ~90 (Ferland 1993). Therefore the [O III]5007 line strength in PKS 0745−191 would need to be about 3.4×10^{-14} ergs s^{-1} cm^{-2} near the nucleus, i.e., 50% brighter than [N II] 6584 Å! Such a strong [O III] line has never been observed in any cooling flow nebula (e.g., Johnstone et al. 1987; Heckman et al. 1989), including PKS 0745−191.

4.3.2. [Fe x] *and Supernovae*

We examine whether supernovae could produce the observed amount of [Fe x] in PKS 0745−191 by shock heating. If each supernova deposited 10^{51} ergs of kinetic energy into the hot gas, at least 1.1 supernovae each year in the central 15 kpc would be required to balance the cooling rate of coronal gas implied by our detection of [Fe x] in PKS 0745−191. Such a high supernova rate would surely be detected, if not in PKS 0745−191, then in similar systems like NGC 1275. (For example, Caldwell & Oemler 1981 report that over a period of 96 months, the entire cluster of Perseus showed only one supernova, and that occurred 140′ from the center.) Furthermore, one might expect that the emission-line spectra of these systems show evidence for supernovae, such as velocity broadened line profiles and [O III]/Hβ ratios $\gtrsim$3–9. Neither are observed. Finally, such a high supernova rate implies a high star formation rate. Assuming that the excess blue emission detected in some cooling flow galaxies (McNamara & O'Connell 1989, 1992; Romanishin 1987) arises from massive stars exclusively and that the IMF for stars is Galactic, these authors derive star formation rates of up to 10 $M_\odot$ yr^{-1} over the central 10 kpc of the galaxies ($H_0 = 50$ km s^{-1} Mpc^{-1} in these calculations). We estimate that this star formation rate corresponds to about five supernovae every 100 yr, a factor of 20 lower than what is necessary to provide heating for the coronal gas.

4.4. *Cooling Condensation Model Constraints*

The most relevant limits are placed on models for the production of the bright optical emission lines (e.g., Hα) (Voit & Donahue 1990; Donahue & Voit 1991; VDS). Their standard model for high column density clouds requires an emission line ratio of [Fe x]/Hα ~ $0.0032 f_c^{-1}$, where f_c is the covering fraction of cool clouds relative to the hot gas, and is, by definition, ≤ 1. Estimating a lower limit on the observed ratio is difficult, because the calculation of an upper limit to the [Fe x] emission requires a priori knowledge of the velocity dispersion of the million-degree gas and the spectrum of the underlying continuum. In this paper, we have assumed that the FWHM of [Fe x] is similar to that of the stronger emission lines of [O I], Hα, and [N II], and that the gas is nearly cospatial.

We can calculate the covering fraction of cool clouds in the regions of the filaments if the Hα from the cool clouds is produced by irradiation of the cool clouds by the cooling, hot gas. Based upon the ratio of [Fe x] to Hα as reported in Table 3, Table 4 lists the derived covering fraction for the filamentary gas in PKS 0745−191 and the upper limits for the covering fractions in the other clusters. These detection and upper limits are consistent with the VDS models but just barely so. Future observations sensitive to lower surface brightness features may challenge the plausibility of this model as more sensitive observations may push the required f_c above unity. If the VDS model is correct, somewhat more sensitive observations should detect [Fe x] in most cooling flow clusters with optical nebulae.

Similar limits can, in principle, be placed on models that produce emission lines by turbulent mixing layers. Such a model has been used to predict large amounts of [O VI] emission (Slavin, Shull, & Begelman 1993) in the Galactic halo. And such models are likely to produce [Fe x] as well, although the detailed spectral signatures of mixing layers in clusters of galaxies have not yet been calculated (although work is in progress). This model requires a similar amount of cooling material as the VDS model. In the turbulent mixing layer model, the gas in the mixed layers, rather than cooling gas, photoionizes the nebular gas. In fast shocks, the gas heated by the shock to nearly X-ray emitting temperatures cools and irradiates the cool filaments. The main difference between these models and the VDS model is that the temperature from which the hot gas cools tends to be at least an order of magnitude lower. But the ultimate source of energy for both models is the gravitational/thermal energy in the X-ray emitting gas. While we expect these models to yield similar [Fe x] luminosities as VDS, the coronal line fluxes predicted by these models are not yet available for comparison with these data.

5. CONCLUSIONS AND SUMMARY

We have reported the marginal detection of coronal [Fe x] in PKS 0745−191 and upper limits based upon the nondetection in four other cluster cooling flows. A reported 7 σ detection in A1795 (AWA) was not confirmed by us, so additional observations of PKS 0745−191 and A1795 by others are necessary to ascertain the strength and reality of these features. Since the luminosity of [Fe x] is directly proportional to the rate of mass cooling through the temperature range of $10^{6.5}$–$10^{5.5}$ K, we can derive the mass cooling rate in the central regions of the brightest cluster galaxy. The mass cooling rates we derive are consistent with (i.e., lower than) the mass cooling rates of gas cooling through hotter temperatures, as measured by X-ray experiments. Lower rates are expected since we are observing only a small portion of the cluster with the spectrograph slit, while the X-ray rates are integrated over the cluster inside the cooling radius.

The detection of [Fe x] in PKS 0745−191 is inconsistent with being produced by photoionization by a central nonthermal source, by hot stars, or by supernovae shocks. We compare our [Fe x] measurements to the ratio of [Fe x]/Hα predicted by cooling condensation models that attempt to explain the luminous nebular emission found in many cluster cooling flows. We find that, while the upper limits are very stringent, they are consistent with the cooling condensation model for producing the nebular emission. Other models for extracting energy from the gravitational potential of the cluster can be subjected to the same scrutiny once predictions for [Fe x] emission are made. The detection of [Fe x] 6374 Å emission reported here strongly supports the existence of cooling gas in at least some clusters of galaxies.

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